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Public Roads

A JOURNAL OF HIGHWAY RESEARCH

An additional cent of gasoline tax, costing the average motorist 13 cents a week, will provide many miles of better highways

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BUREAU OF PUBLIC ROADS

U. S. DEPARTMENT OF COMMERCE

E. A. STROMBERG, Editor

The Gasoline Tax in Relation to Automobile Operation and Highway Costs

BY THE RESEARCH REPORTS BRANCH
BUREAU OF PUBLIC ROADS

Reported by E. M. COPE, Chief, Highway Statistics Section and L. L. LISTON, Transportation Economist

Unit costs of highway construction and maintenance have almost doubled in the last 10 years, considerably exceeding the 77-percent increase in the basic cost of living. The price of gasoline, excluding tax, rose 62 percent in the same 10 years, but since the tax on gasoline rose less than 13 percent during this period the net effect felt by the motorist in his purchases of gasoline was an increase of only 47 percent in the total of price plus tax.

There has been a substantial increase in revenue for highways over the 10-year period, resulting from the tremendous growth in the number of motor vehicles. This has been nullified, however, by the extreme increase in highway costs and the contrastingly small one in tax rates. Current revenue will buy no more highway work than did the 1940 revenue. Yet the need is far greater, for the constantly multiplying number of vehicles continually intensifies our traffic problems.

The public apparently does not have a clear picture of the relation of taxes to the total cost of owning and operating an automobile. An analysis for a typical passenger car indicates that the taxes represent only 11 percent of the total ownership and operation costs—less than any other major item of cost involved. Put in practical terms, of the 6.6 cents per mile it costs to own and operate an automobile, all taxes combined represent seven-tenths of a cent.

The gasoline tax accounts for only 6½ percent of the total cost of owning and operating a car, or four-tenths of a cent per mile, and the tax rate is actually lower in proportion to individual income now than it was in 1940. Each cent of the gasoline tax rate costs the average motorist seven-hundredths of a cent per mile, or about 13 cents a week—just about 1 percent of the total ownership and operation cost.

GASOLINE TAXES constitute a very small part of the total cost of owning and operating an automobile, and revenues from gasoline taxes are falling far short of needed highway construction and maintenance expenditures. While other prices and costs have nearly doubled in the past 10 years, the tax on gasoline has increased only 12.7 percent. It is the purpose of this study to compare trends in gasoline taxes, costs of operating an automobile, and costs of constructing and maintaining highways.

A previous article in PUBLIC ROADS[1] reported a study of gasoline price and tax increases during a 30-month period ending June 30, 1948. Although there were substantial gasoline price increases in all States and gasoline tax increases in 12 States during that period, these increases had no measurable effect on consumption of gasoline. In the 1949 study, however, no effort was made to establish the relation between gasoline costs, total vehicle operating costs, and the portion of the vehicle operator's dollar that goes for road-user taxes. Such comparisons are made here.

Gasoline Prices and Taxes

Gasoline prices have continued to increase since 1948, and there have been increases in gasoline taxes in some States. The increases in gasoline prices (excluding taxes) and in State gasoline taxes during the 54-month period from January 1946 to June 1950 are shown in figure 1. This figure is an extension of figure 2 in the 1949 study, which covered the 30 months from January 1946 to June 1948. The findings for the longer period are in such complete agreement with those of the original study that reiteration of the conclusions in detail would be needless repetition.

The earlier study established that no gasoline tax increase has had a measurable effect on the consumption of gasoline, and none within reasonable contemplation appears likely to do so. Theoretically, any rise in the cost of operating automobiles should have some restraining effect on the amount of vehicle use. The reason that no effect has been noted is rather obvious—the gasoline tax constitutes only about 6.5 percent of the total cost of operating an automobile (as will be shown later), and has actually been declining in terms of its relation to the total cost.

There were net tax increases, during the 54-month period, of from 1/2 cent to 2 cents per gallon in 23 States, and a net tax decrease of 1 cent per gallon in one State. There were net price increases, excluding taxes, in all States during the same period. In Utah the price increase was only 1/2 cent per gallon, and in California the net price increase was only 2 cents per gallon. In other States, however, the net price increases were much higher—ranging from 3.4 cents per gallon in Arizona to 8.5 cents per gallon in Wyoming. Available information indicates that the Utah and California increases were relatively small because of intense competitive conditions in those areas.

Relative Cost of Gasoline

It has never been possible to measure the extent of the effect of operating costs on vehicle ownership and use. Much of the discussion and publicity on the point has centered around the cost of gasoline, probably because this is an item with which the public comes in daily contact. Gasoline taxes have assumed a disproportionate importance to the public because considerable publicity has been given to gasoline prices and taxes when matters pertaining to them have been under study by State legislatures, and to the allegation that "gasoline is cheap—only the tax is high."

The emphasis on gasoline taxes has tended to obscure the fact that many items of the cost of operating a motor vehicle considerably exceed gasoline tax payments. It is not generally recognized that both gasoline prices and gasoline tax rates have risen more slowly than general price levels. The average retail price of gasoline in 1940, including taxes, was 18.4 cents per gallon. During the 10 years to 1950 the retail price alone, excluding taxes, increased 62 percent. It is worth noting that this increase, though substantial, was considerably less than the 77-percent increase in the cost of living reflected in the Bureau of Labor Statistics

[1] *The effect of tax increases on gasoline consumption*, by E. M. Cope and L. L. Liston. PUBLIC ROADS, Vol. 25, No. 7, March 1949, p. 138.

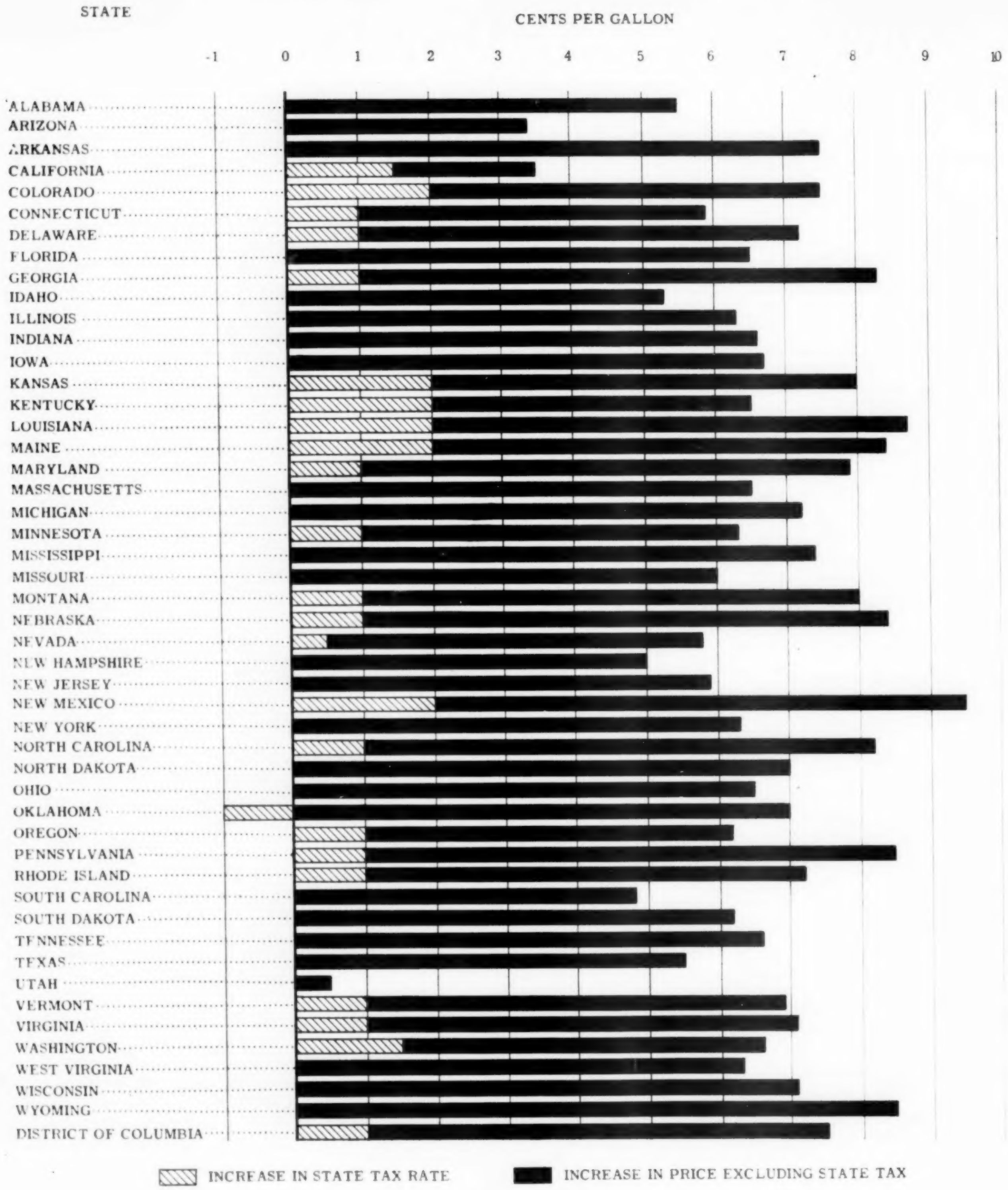

Figure 1.—Gasoline price and tax increases, January 1, 1946–June 30, 1950

index. In the same 10-year period the weighted average of State and Federal gasoline taxes rose only 12.7 percent. Thus, due to the relative stability of gasoline taxes, the total cost of gasoline to the consumer increased only 47.3 percent. Since wages have risen considerably more than the cost of gasoline, the consumer is actually in a better position now than in 1940 with respect to his purchases of gasoline. The percentage increase in the cost of gasoline, even though it was approximately five times as great as that for gasoline taxes, was still 20 percent less than the percentage increase in the cost of living reported by the Bureau of Labor Statistics. A comparison of gasoline taxes and prices in 1940 and in 1950 is given in table 1.

Highway Costs

The economic factors that brought about increased costs of gasoline also caused increased costs of raw materials, wages, transportation, and other components of the total price of motor vehicles, gasoline, and associated products. Likewise, they brought about sharp increases in the costs of constructing highways—a rise of 97 percent in the 10-year period from 1940 to 1950. The increases in the costs of construction are reflected in table 2.

During the same period highway maintenance costs rose 87 percent. This figure is a composite of the relative increases from 1940 to 1950 in the unit costs of the principal items of maintenance, which were as follows: Labor, 114.27 percent; materials, 56.72 percent; equipment, 72.73 percent; and overhead, 67.10 percent.

Table 1.—*Gasoline price[1] and tax changes, 1940-50*

	Price, excluding tax	Tax	Total price	Relation of tax to total price
	Cents	*Cents*	*Cents*	*Percent*
1940	12.9	5.5	18.4	29.9
1950	20.9	6.2	27.1	22.9
Percentage change	+62.0	+12.7	+47.3	−7.0

[1] Prices in effect in the capital cities of the States except for Maryland and Oregon, where the prices are for Baltimore and Portland, respectively.

Table 2.—*Changes in unit costs of highway construction, 1940-50*

Item	1940	1950	Increase
			Percent
Common excavation: bid price, cu. yd	$0.21	$0.34	61.9
Concrete pavement: bid price, sq. yd	1.68	3.66	117.9
Structures:			
Reinforcing steel: bid price, lb	.045	.100	122.2
Structural steel: bid price, lb	.063	.139	120.6
Concrete: bid price, cu. yd	19.170	44.620	132.8
Composite index			97.0

Figure 2 shows the relative increases in the cost of living, the price of a new automobile, the price of gasoline (excluding tax), the gasoline tax rate, and the unit costs of highway construction and maintenance. It will be noted that the price of gasoline did not increase as much as either the cost of living or the price of a new automobile. But even the petroleum industry, generally considered to be one of the most efficient in our economy, found it necessary to increase the price of gasoline five times as much (on a percentage basis) as gasoline taxes were increased.

Automobile Operating Costs

State gasoline taxes, which are the principal source of revenue for highways, cost the average automobile user about 65 cents a week. This fact is of limited significance until it is related to total costs of vehicle operation. In order to establish the relation, an estimate of the cost of owning and operating an automobile is presented in table 3. It is not based on actual records for any particular vehicle or group of vehicles, but the figures are believed to be typical, at mid-1950 prices, for average operation of the type of automobile considered.

The estimate is based on a low-priced 1950-model four-door sedan built by a leading manufacturer, and covers an assumed 10-year life for the vehicle. The automobile is assumed to be registered in Baltimore, Md., and subject to normal taxes in that area. Although the mileages, operating costs, and other factors in the estimate are believed to be reasonable, they are not purported to be averages or for an average vehicle. Data for such purposes are not available in sufficient coverage. The essential factors of the estimate are stated in the notes below table 3.

In estimating expenditures for repairs and maintenance, the *Service Job Analysis* estimate compiled by Motor Service Magazine was used. This analysis lists the number of jobs of different kinds done by car dealers and independent repair shops for several years. A sample group of jobs, comprising more than two-thirds of the total listed, was chosen as representative of the maintenance and repair work which would be done on a typical automobile during the 10-year period. These items range from major repairs such as a complete engine overhaul to minor maintenance items like washing and lubrication. The frequency of the jobs listed in the *Service Job Analysis* and the experience of men familiar with automotive maintenance and service were used as guides to the number of times each job would be required during the life of the car. Costs, including parts, were then obtained from the most recent flat-rate manuals, and the prices of parts as listed in the manual were checked locally to determine any necessary adjustments for the Baltimore area.

The expenditures for major items—replacement tires, motor overhaul, painting, for example—are distributed over a period of years, rather than being charged entirely to the year of actual expenditure, because the benefit of each expenditure extends beyond the year in which it was made. The cost of the motor overhaul, for instance, occurs in the seventh year but is distributed over the seventh through the tenth years.

No costs for car financing, for fines and forfeitures, or for automobile club membership are included, nor is any interest on the investment included. Although these items may add substantially to the cost of owning and operating an automobile in some instances, the wide variance in their application among motorists makes it impractical to include them in this study.

Relation of Cost Elements

It is somewhat surprising to note that the several factors entering into the cost of operating the vehicle tend to keep the cost per mile within the rather narrow range of 7.35 cents in the first year to 5.24 cents[2] in the tenth year. The high depreciation and insurance costs of the first few years are offset to a considerable degree by greater mileage and low maintenance costs, and by absence of tire replacement expenditures. Although the estimate is based on the assumption that the vehicle will be scrapped after 10 years of use, the probability is, in a period in which there is a relative shortage of vehicles, that it would pass into the hands of a marginal user and continue in service. It is not likely, however, that the over-all cost per mile would

[2] These costs are all based on mid-1950 price levels. Practically all items of cost, with the exception of taxes, have increased since that time.

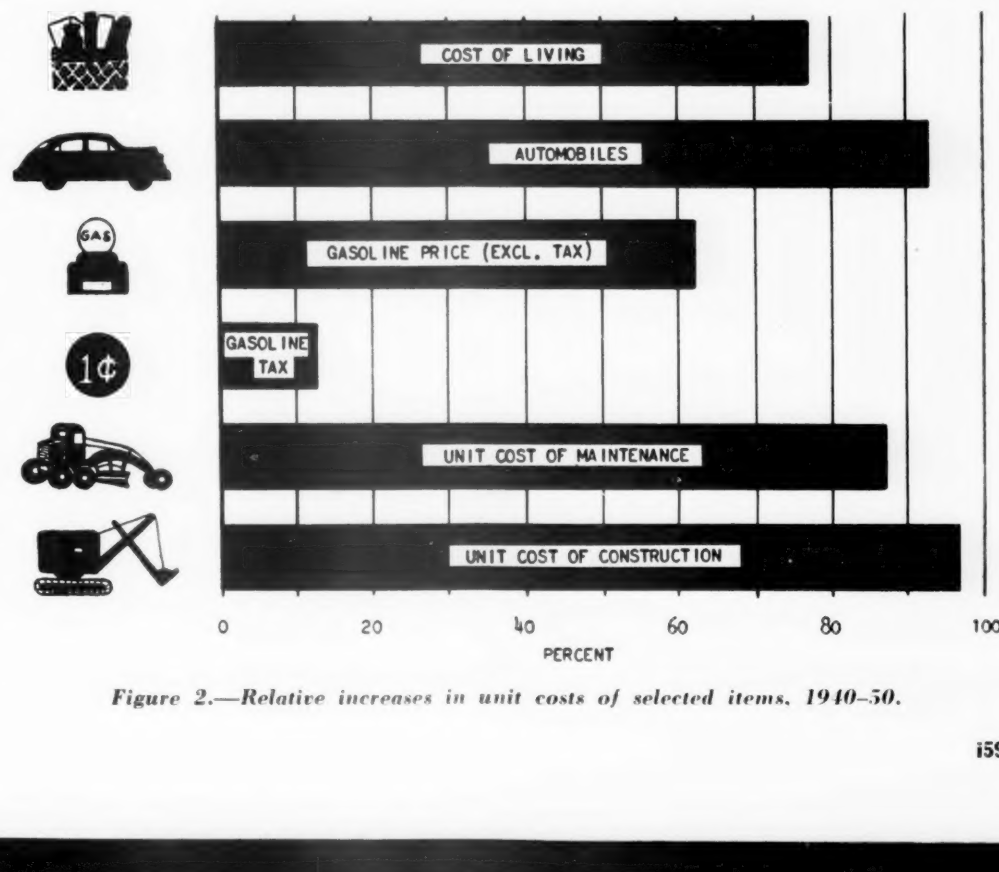

Figure 2.—Relative increases in unit costs of selected items, 1940–50.

Table 3.—*Estimated cost of owning and operating an automobile*

Item	First year (12,500 miles)		Second year (12,000 miles)		Third year (11,000 miles)		Fourth year (10,000 miles)		Fifth year (10,000 miles)		Sixth year (9,500 miles)		Seventh year (9,500 miles)		Eighth year (9,000 miles)		Ninth year (8,500 miles)		Tenth year (8,000 miles)		Ten-year period (100,000 miles)	
	Total cost	Cost per mile	Total cost	Cost per mile	Total cost	Cost per mile	Total cost	Cost per mile	Total cost	Cost per mile	Total cost	Cost per mile	Total cost	Cost per mile	Total cost	Cost per mile	Total cost	Cost per mile	Total cost	Cost per mile	Total cost	Cost per mile
	Dollars	*Cents*	*Dollars*	*Cents*	*Dollars*	*Cents*	*Dollars*	*Cents*	*Dollars*	*Cents*	*Dollars*	*Cents*	*Dollars*	*Cents*	*Dollars*	*Cents*	*Dollars*	*Cents*	*Dollars*	*Cents*	*Dollars*	*Cents*
Costs excluding taxes:																						
Depreciation	360.00	2.880	330.00	2.750	200.00	1.818	125.00	1.250	100.00	1.000	75.00	0.790	75.00	0.790	65.00	0.722	40.00	0.471	30.00	0.375	1,400.00	1.400
Repair and maintenance	46.25	.370	57.74	.481	87.02	.791	112.04	1.120	113.30	1.133	173.49	1.826	159.18	1.676	129.09	1.434	70.36	.828	36.08	.451	984.55	.984
Replacement tires and tubes							26.00	.260	25.00	.250	25.00	.263	22.00	.231	22.00	.244	20.00	.235	20.00	.250	160.00	.160
Accessories	4.50	.036	14.84	.123	14.84	.134	14.84	.149	14.83	.148	14.83	.155	14.83	.155	14.83	.165	14.83	.174	14.83	.184	138.00	.138
Gasoline	163.46	1.307	156.80	1.307	143.67	1.307	130.73	1.307	130.73	1.307	124.07	1.307	124.07	1.307	117.60	1.307	111.13	1.307	104.47	1.307	1,306.73	1.307
Oil	16.94	.136	16.17	.135	16.94	.154	14.25	.143	15.68	.157	16.08	.170	12.71	.134	12.32	.137	9.69	.114	11.40	.143	142.18	.142
Insurance	116.00	.928	116.00	.967	116.00	1.055	111.00	1.110	111.00	1.110	59.00	.621	59.00	.621	59.00	.656	59.00	.694	59.00	.737	865.00	.865
Garaging, parking, tolls, etc	90.00	.720	90.00	.750	90.00	.818	90.00	.900	90.00	.900	90.00	.947	90.00	.947	90.00	1.000	90.00	1.059	90.00	1.125	900.00	.900
Total	797.15	6.377	781.55	6.513	668.47	6.077	623.86	6.239	600.54	6.005	577.47	6.079	556.79	5.861	509.84	5.665	415.01	4.882	365.78	4.572	5,896.46	5.896
Taxes and fees:																						
State:																						
Gasoline	41.70	0.333	40.00	0.333	36.65	0.333	33.35	0.333	33.35	0.333	31.65	0.333	31.65	0.333	30.00	0.333	28.35	0.333	26.65	0.333	333.35	0.333
Registration	10.00	.081	10.00	.083	10.00	.091	10.00	.100	10.00	.100	10.00	.105	10.00	.105	10.00	.111	10.00	.119	10.00	.125	100.00	.100
Titling	31.00	.248																			31.00	.031
Property	5.00	.040	5.00	.042	5.00	.045	5.00	.050	5.00	.050	5.00	.053	5.00	.053	5.00	.056	5.00	.059	5.00	.062	50.00	.050
Subtotal	87.70	.702	55.00	.458	51.65	.469	48.35	.483	48.35	.483	46.65	.491	46.65	.491	45.00	.500	43.35	.511	41.65	.520	514.35	.514
Federal:																						
Gasoline	12.51	.100	12.00	.100	11.00	.100	10.00	.100	10.00	.100	9.50	.100	9.50	.100	9.00	.100	8.51	.100	8.00	.100	100.02	.100
Oil	.66	.005	.63	.005	.66	.006	.75	.007	.83	.009	.72	.007	.50	.005	.48	.005	.51	.006	.60	.008	6.34	.007
Automobile, tires, parts, etc	21.00	.168	19.16	.160	11.73	.107	9.47	.095	9.11	.091	7.32	.077	6.76	.071	6.22	.069	4.02	.047	3.40	.043	98.19	.098
Subtotal	34.17	.273	31.79	.265	23.39	.213	20.22	.202	19.94	.200	17.54	.184	16.76	.176	15.70	.174	13.04	.153	12.00	.151	204.55	.205
Total	121.87	0.975	86.79	0.723	75.04	0.682	68.57	0.685	68.29	0.683	64.19	0.675	63.41	0.667	60.70	0.674	56.39	0.664	53.65	0.671	718.90	0.719
Total of all costs	919.02	7.352	868.34	7.236	743.51	6.759	692.43	6.924	668.83	6.688	641.66	6.754	620.20	6.528	570.54	6.339	471.40	5.546	419.43	5.243	6,615.36	6.615

Automobile.—The vehicle considered was a 1950-model four-door sedan, costing $1,450 excluding accessories and taxes. The junk value of the automobile at the end of 10 years was placed at $50.00.

Accessories.—Accessories provided included heater, three sets of seat covers, and side mirror.

Maintenance and repair.—Maintenance and repair covered routine lubrication, brake adjustment, replacement of minor parts such as spark plugs, ignition points, wiper blades, fan belts, etc. Additional items assumed were brake relining twice, clutch replacement twice, generator and starter overhaul once, universal joint replacement once, complete motor overhaul once, one new axle, one complete repaint job, kingpin and bushing replacement twice, and other intermediate and minor repairs. Fender and body work averaging about $8.50 per year was also included.

Replacement tires and tubes.—Purchase of 8 new tires and tubes during the life of the car was assumed.

Gasoline and oil.—Gasoline consumption was set at 15 miles per gallon; oil consumption at 422 quarts in the 10-year period, with cost and amount adjusted to the age and condition of the car.

Insurance.—Insurance coverage of $15,000/$30,000 public liability, $5,000 property damage, and comprehensive fire and theft, etc., was assumed for the full 10 years; $50-deductible collision insurance for the first 5 years.

Garaging, parking, tolls.—Monthly charges of $5.00 for garage rental or indirect cost of owner's garage and $2.50 for parking and toll fees were included.

Taxes.—Taxes represented are Federal and Maryland gasoline taxes at 1½ and 5 cents per gallon, respectively; Maryland registration fee of $15.00 per year, including the property-tax component; Maryland titling tax at 2 percent of retail price; Federal excise taxes on motor vehicles, tires, tubes, and accessories; and Federal tax of 6 cents per gallon on oil.

Benefit period.—The costs of certain major items are spread over a period of benefit rather than being charged entirely to the year in which the expenditure was actually made.

be appreciably reduced, provided the vehicle was maintained at a level to assure minimum safety and comfort.

Of the 7.35 cents-per-mile total operating costs in the first year of the estimate, the cost of gasoline, including all taxes, was 1.74 cents per mile. Gasoline taxes amounted to only 0.433 cent per mile, or 0.067 cent per mile for each cent of the tax rate. Thus each increment of 1 cent of tax adds less than 1 percent to the total cost of operating the vehicle. Under these circumstances it can be understood why no tax increase has ever made a measurable difference in the highway use of gasoline.

There is good reason to believe that the average motorist does not understand the true relation between his vehicle ownership and operation costs and the tax monies expended for the highways he uses. It would probably come as a surprise to him to learn that the total amount he pays in highway-user taxes, toward the construction and maintenance of the roads over which his automobile is operated, is substantially exceeded by all of the other major items of vehicle operation cost. This fact is presented graphically in figure 3.

Because of the widely quoted statements made in organized opposition to proposed increases in gasoline taxes in several States, most automobile owners might be reluctant to believe that each cent of the gasoline tax accounts for only 1 percent of total vehicle operating costs. The average motorist is also probably not aware that highway improvements made possible by each additional cent of gasoline tax not only add to the safety and convenience of motor-vehicle travel, but also reduce operating costs through improved surfaces, grades, and alinement, reduced mileage, and lessened traffic congestion.

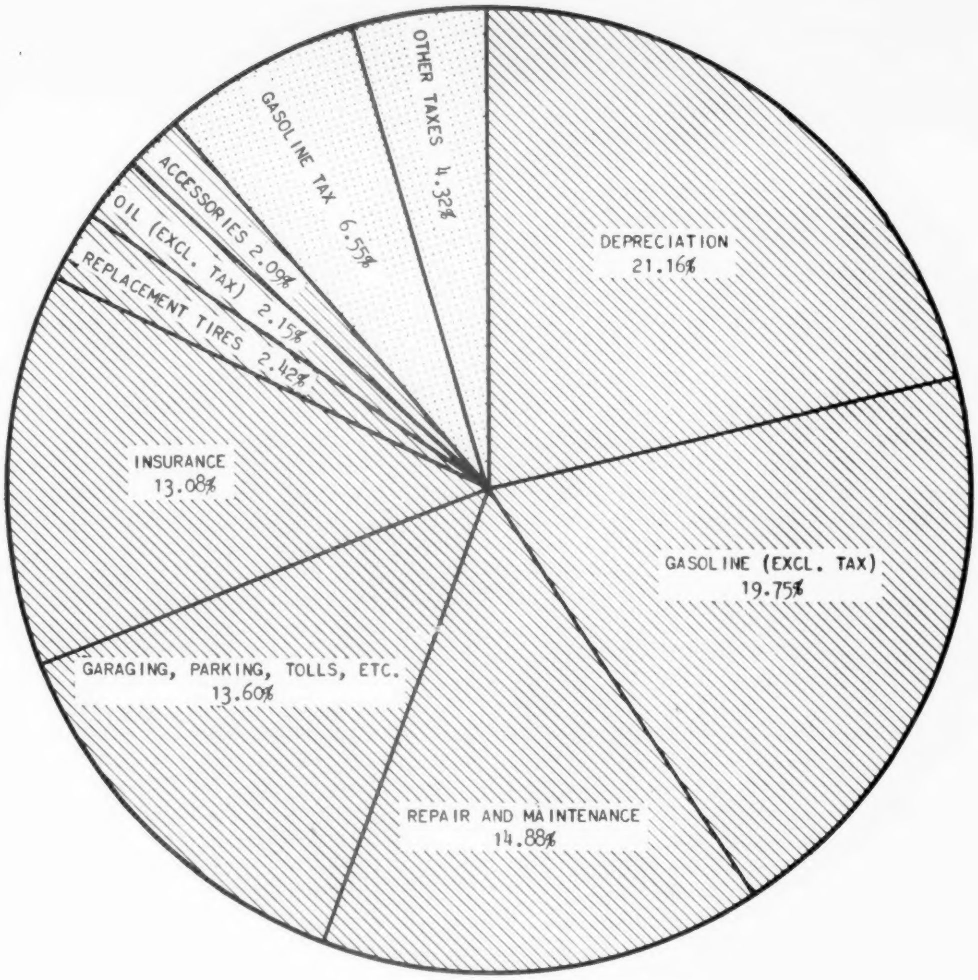

Figure 3.—Distribution of automobile ownership and operation costs.

Highway Revenues and Needs

Although road-user tax rates have risen less than any other automotive operating cost during the past 10 years, the revenues from them have increased substantially as a result of the large increase in the number of vehicles. The increases in highway construction and maintenance costs, however, have so reduced the value of the highway dollar that total revenues today will provide only about the same number of units of construction and maintenance that were purchased with 1940 revenues. While this reduction in the purchasing power of revenues is undoubtedly the most serious single problem now facing highway authorities, there are two others of almost equal importance—the mounting volume of traffic for which highway capacity must be provided, and the higher standards to which today's highways must be constructed to allow safe travel for present speeds and loads. If prices had remained at 1940 levels, current revenues would be adequate to maintain our then-existing system of roads and streets, and to improve and expand the system as needed for the greatly increased number of vehicles. But with present revenues able to purchase only the amount of construction and maintenance that was purchased with 1940 revenues, highway authorities are finding it impossible to provide adequate highway capacity for a 51-percent greater number of vehicles and a 60-percent increase in traffic volume.

Effect on the Individual

Discussions of road-user taxes are frequently of a technical nature not readily understood by the automobile owner. He is exposed to diametrically opposite views and irreconcilable statements. The allegation is made that "gasoline is cheap—only the tax is high." Yet the price of gasoline (excluding tax) now represents 19.8 percent of total automobile operating costs, while the gasoline tax is only 6.5 percent, and the tax portion of the total price of gasoline has decreased approximately 7 percent during the past decade. The motorist appears to be willing to pay tolls that cost the equivalent of an additional 15-cent tax per gallon for the use of controlled-access toll highways, but seems not to understand the relatively low cost, per vehicle-mile, of adequate free highways. When automotive taxes and highway programs are discussed, he unfortunately sees figures only in large multiples of any amounts familiar to him. Being impressed by their magnitude, he does not realize that the portion of these amounts that he pays as an individual is actually very small.

In most States there are certain minimum amounts that must be spent for highway administration, equipment, and maintenance. After these requirements have been met, any funds remaining are available for construction. Small increments in tax allocations under these circumstances can amount to relatively large increases in funds available for construction. If the 19 States having gasoline tax rates of less than 5 cents per gallon were to increase their rates 1 cent, the State funds available for highway construction would be increased, on the average, by more than 40 percent. In over two-thirds of these States the construction funds would be increased an average of more than 50 percent. Yet this increase would cost the motorist (at 15 miles per gallon), only 0.067 cent per mile, or about 13 cents a week.

Volume Changes in Sand-Gravel Concrete

BY THE PHYSICAL RESEARCH BRANCH
BUREAU OF PUBLIC ROADS

Reported by F. H. JACKSON, Principal Engineer of Tests and A. G. TIMMS, Senior Materials Engineer

Abnormal expansion, as evidenced in map-cracking, has been observed in concrete pavements built with sand-gravel aggregate in some midwestern States. Tests with this and two other aggregates of widely different mineral composition, combined with different types of cement and subjected to various weathering conditions, produced effects in the laboratory which correlated with those observed in the field.

Expansion of concrete specimens made with sand-gravel was much greater than that of similar specimens containing the other aggregates, and appeared to be due to some characteristic related to the mineral composition of the sand-gravel. The magnitude of the expansion was markedly influenced by the properties of the cements used.

The addition of crushed limestone to the sand-gravel, producing a normally graded coarse aggregate which contained about 50 per cent calcareous material, eliminated the abnormal expansion entirely.

Introduction

ABNORMAL EXPANSION of concrete pavement with resultant so-called "map-cracking" of the surface, which has been widely observed in certain midwestern states, particularly Kansas and Nebraska, prompted the Bureau of Public Roads about 10 years ago to initiate a series of tests to determine whether these effects could be reproduced in the laboratory and, if so, just what combinations of materials produced them and what steps might be taken to eliminate the trouble. The tests involved the measurement of changes in length of concrete specimens containing aggregates from three sources: The Platte River in Nebraska, Chicago, Ill., and Long Island, N. Y.

The Platte River aggregate was representative of a class of materials locally known as "sand-gravel," which contains only a small percentage of particles larger than 3/8 inch in size. Most of the concrete pavements in these areas which have shown distress were constructed with this type of aggregate. The aggregates from Long Island and the Chicago area were selected as representative of two sources differing widely in mineralogical composition but possessing excellent service records in concrete.

Each of the three aggregates, in three different gradations, was used in combination with each of four cements. All of the latter met the usual American Society for Testing Materials requirements for type I cement, and two of them in addition met both the A.S.T.M. requirements for type II cement and the requirements of the Board of Water Supply of New York City.

The concrete specimens made from these aggregates and cements were subjected successively to various types of laboratory weathering cycles which involved alternate wetting and drying together with alternate heating and cooling, but without freezing and thawing. In general the program followed the pattern set by W. E. Gibson, of the Kansas State Highway Laboratory, who began studying this problem as early as 1932. The results of Gibson's findings were reported before the Highway Research Board in 1938.[1]

A progress report giving the results of the studies made by the Bureau over a 2-year period was presented before the Highway Research Board in 1942.[2] This was followed in 1949 by a final report which reviewed the earlier work and gave the results of further measurements up to a total of 9 years of exposure.[3]

In the report presented here the data and discussions of the latter two papers have been combined into a single report which is intended to serve as a complete and final report of this investigation as it was originally planned.

Summary of Observations

The principal indications of these tests were as follows:

1. A laboratory weathering cycle which involved immersion in water at 70°F. for 24 hours followed by drying in air at 130°F. for 24 hours produced length changes and visual effects (such as map-cracking) in concrete test specimens that correlated with the behavior of similar concrete in the field.

2. Concrete specimens containing only the Platte River sand-gravel aggregate developed, in general, much larger expansions than similar concrete containing the other two aggregates. In many cases the appearance of map-cracks on the surfaces of the specimens provided visual evidence of abnormal expansion.

3. The abnormal expansion that developed when the Platte River sand-gravel was used as total aggregate appeared to be due to some characteristic related to its mineral composition rather than to its grading or to the high cement content normally used with this type of material.

4. In the concrete specimens containing the Platte River sand-gravel as total aggregate, the magnitude of the expansions was influenced to a marked degree by certain differences in the properties of the four cements used. However, there was no relation observed in this study between the amount of expansion and any of the physical or chemical properties of the cements.

5. Adding crushed limestone with a maximum size of 1½ inches to the Platte River

Figure 1.—Typical map-cracking of sand-gravel concrete pavement.

[1] *A study of map cracking in sand-gravel pavements*, by W. E. Gibson. Proceedings of the Highway Research Board, Vol. 18, Part I, 1938, p. 227.
[2] *Volume changes in sand-gravel concrete*, by F. H. Jackson and W. F. Kellermann. Proceedings of the Highway Research Board, Vol. 22, 1942, p. 252.
[3] *Volume changes in sand-gravel concrete*, by F. H. Jackson and A. G. Timms. Proceedings of the Highway Research Board, Vol. 29, 1949, p. 212.

Table 1.—*Chemical and physical properties of portland cements*

	Portland cement			
	1	2	3	4
Chemical analyses (percent):				
Silica (SiO_2)	21.95	20.60	22.71	23.16
Alumina (Al_2O_3)	5.57	7.74	4.72	5.11
Ferric oxide (Fe_2O_3)	3.20	2.65	4.60	3.67
Lime (CaO)	62.70	62.70	62.54	61.28
Magnesia (MgO)	2.99	2.77	2.77	1.15
Sulfuric anhydride (SO_3)	1.70	1.79	1.51	1.32
Sodium oxide (Na_2O)	.26	.36	.19	.26
Potassium oxide (K_2O)	.67	.56	.43	.47
Alkali calculated as Na_2O	.70	.73	.47	.57
Water-soluble alkali calculated as Na_2O	.52	.38	.18	.21
Computed compound composition [1] (percent):				
Tricalcium silicate (C_3S)	42	38	39	42
Dicalcium silicate (C_2S)	32	31	36	35
Tricalcium aluminate (C_3A)	9	16	5	7
Tetracalcium alumino ferrite (C_4AF)	10	8	14	11
Calcium sulfate ($CaSO_4$)	2.8	3.0	2.5	2.1
Physical properties:				
Specific surface (Wagner) ... $cm.^2$ per gm	1,850	1,705	1,965	1,815
Sugar test (Merriman):				
Neutral point ... ml	33.2	36.8	2.7	2.7
Clear point ... ml	48.1	57.5	2.7	2.7
Autoclave expansion ... percent	.09	.42	.05	.01
Normal consistency ... percent	24.5	25.5	23.5	24.0
Tensile strength (1:3 mortar):				
At 7 days ... lb. per sq. in.	305	340	315	360
At 28 days ... lb. per sq. in.	375	420	445	435

[1] The compound compositions given are in "shorthand" form.

sand-gravel, in the proportion of about 50 percent by weight of the total aggregate, eliminated the abnormal expansion. This was true for all four of the cements included in this investigation.

6. Concrete containing the sand and gravel from Long Island, an aggregate essentially siliceous in character, developed greater expansions than similar concrete containing the essentially calcareous sand and gravel from Chicago. This applied to all three gradings in which these materials were used and to all four cements.

7. Both the specimens containing a blend of the Platte River sand-gravel and crushed limestone and the specimens containing the Long Island sand and gravel, when used in normal gradation in combination with the two cements relatively high in computed tricalcium aluminate, developed greater expansions than similar specimens containing the two cements having relatively low percentages of this compound. However, this trend was not noted in the specimens containing the sand and gravel from Chicago.

8. These tests indicate that aggregate characteristics other than size and grading, such as particle shape, surface texture, mineral composition, etc., will affect the amount of cement necessary to maintain a given consistency, using a fixed water-cement ratio, to a much greater extent than has been commonly assumed.

Use of Sand-Gravel

The lack of suitable deposits of coarse aggregate for concrete in many parts of Kansas and Nebraska, and in certain sections of western Missouri and Iowa, has led to the extensive use of a naturally occurring mixture of sand and fine gravel as total aggregate for concrete work in these regions. This material, substantially all of which passes a ⅜-inch sieve, is known locally as "mixed aggregate" or "sand-gravel." Concrete in which it is used is known as sand-gravel concrete to distinguish it from concrete containing normally graded coarse aggregate, which is called locally "fine-and-coarse-aggregate" concrete.

The sand-gravels vary somewhat in mineral composition from place to place, but in general they are composed of quartz and granitic materials with varying amounts of feldspar and very little limestone or other calcareous material.

The local sand-gravel deposits, widely distributed along the beds of such streams as the Arkansas and Kaw Rivers in Kansas and the Platte River in Nebraska, furnish the only type of aggregate available in many parts of these States. These aggregates in general are reasonably well graded from ⅜-inch down, although the process of washing results in a deficiency in the finer sand sizes, particularly in the material passing the No. 50 sieve. The availability of these deposits makes them exceedingly attractive from the economic point of view, even though the fine grading has in some cases necessitated the use of cement contents as high as 7.5 to 8.0 sacks per cubic yard in order to meet requirements for design strength.

The belief that these materials were of satisfactory quality, and the fact that they were so readily available, resulted in their use in the construction of a substantial mileage of concrete pavements in Kansas and Nebraska. For example, most of the

Table 2.—*Grading, specific gravity, weight, and absorption of aggregates*

	Grading 1 (as used)	Grading 2 (as used)	Grading 3 [1]		
			Aggregate		Combined (as used)
			Fine	Coarse	
Grading: percentage retained on—					
1½-inch sieve				0	0
¾-inch sieve	0	0		55	36
⅜-inch sieve	5	5		83	54
No. 4 sieve	10	10	0	100	64
No. 8 sieve	30	30	20	100	72
No. 16 sieve	55	50	40	100	79
No. 30 sieve	80	65	60	100	86
No. 50 sieve	95	80	84	100	94
No. 100 sieve	100	95	97	100	99
Fineness modulus	3.75	3.35	3.01	7.33	5.84
Bulk specific gravity (dry):					
A—Platte River	2.61	2.61	2.61	[1] 2.60	
B—Long Island	2.65	2.65	2.66	2.63	
C—Chicago	2.62	2.62	2.62	2.65	
Weight, dry rodded (lb. per cu. ft.):					
A—Platte River	116	122	118	[1] 101	
B—Long Island	112	117	109	111	
C—Chicago	1[illegible]0	117	110	103	
Absorption (percent):					
A—Platte River	0.32	0.32	0.27	[1] 1.17	
B—Long Island	.29	.23	.31	.30	
C—Chicago	2.34	1.98	1.69	1.79	

[1] For this grading, where the Platte River combination was used, the materials include a combination of Platte River aggregate, grading 1, and sufficient crushed limestone to give desired grading.

Table 3.—*Other physical properties of aggregates*

	Aggregate		
	A—Platte River	B—Long Island	C—Chicago
Soundness (sodium sulfate loss at 5 cycles) [1] ... percent	3.2	4.4	10.2
Resistance to abrasion (Los Angeles loss for grading D) [2] ... percent	29.0	26.8	21.7
Organic matter (color test)	OK	OK	OK
Mortar strength ratio, 7 days [3]	.94	1.05	.90

[1] Weighted average loss based on grading 1.
[2] A.S.T.M. standard C 131–39, tentative revision 1942.
[3] A.S.T.M. standard C 87–42.

Table 4.—*Mineral analyses of aggregates*

Rock or mineral	Percentage composition for each sieve size indicated									Average composition[1]	
	1½- to ¾-inch	¾- to ⅜-inch	⅜-inch to No. 4	No. 4 to No. 8	No. 8 to No. 16	No. 16 to No. 30	No. 30 to No. 50	No. 50 to No. 100	Passing No. 100	Gravel	Sand
A—Platte River aggregate:											
Granite[2]	(3)	59	51	32	8	3	T(4)			55	7.1
Feldspar		19	25	40	34	21	11	4	3	22	18.8
Quartz		8	19	25	55	74	89	96	94	13.5	72.1
Chert		3	T	T	T	1	T	T	3	1.5	.6
Quartzite		4	3	1	3					3.5	.6
Sandstone		3	1	1	T	1				2	.3
Ferruginous sandstone		2								1	
Rhyolite		T	T	T	T					T	T
Epidosite		T								T	
Hornblende schist		T								T	
Andesite				T							T
Hornblendite					T						T
Biotite							T				T
B—Long Island aggregate:											
Quartz	87	71	74	83	92	93	95	96	98	77.3	92.8
Quartzite	13	16	9	5	4	3	T	1		12.6	2.2
Schistose quartzite		1	3	2						1.3	.3
Hornblende schist		1								.3	
Feldspar		3								1	
Ferruginous sandstone		4	3							2.3	
Mica schist		4	3	4	1					2.3	.8
Granite			6	4	1	3	T			2	1.3
Gneiss			2	2	1	1				.6	.7
Sandstone			T							T	
Garnet schist				T							T
Biotite							T				.3
Muscovite							T				T
Hornblende							T				.3
Sericite								T			T
C—Chicago aggregate:											
Dolomite	82	98	89	95	92	91	72	61	78	89.6	81.5
Quartzite	11		3				3	4		4.6	1.1
Trap	7		4	2	2	3	1	1	T	3.6	1.5
Limestone		2								.6	
Chert			4	2	4	2				1.3	1.3
Quartz				1	2	4	24	34	22		14.5

[1] Gravel size considered as material retained on No. 4 sieve, sand as that passing No. 4 sieve.
[2] Consists of quartz and feldspar with occasional biotite.
[3] This size Platte River aggregate not available.
[4] Trace.

original concrete pavement along U.S. 30 in Nebraska was of this type. This route follows the Platte River for many miles and the local sand-gravel is available at almost any point along the road with very short haul.

Unfortunately, the sand-gravel type of concrete pavement has not proved entirely satisfactory. Defects in the form of map-cracking of the surface frequently developed on many sections within a few years. Sometimes these defects led to progressive failure of a type which eventually required repair or replacement of the affected areas. A survey of Nebraska pavements conducted in 1939 by the Bureau of Public Roads in cooperation with the State Department of Roads and Irrigation revealed that about one-third of the approximately 500 miles of sand-gravel concrete pavement surveyed, all of which was constructed between 1925 and 1935, had developed map-cracking of a type which appeared to be progressive. In contrast to these observations on sand-gravel concrete, no evidence of map-cracking had developed up to 1939 on any of the pavements laid with fine-and-coarse aggregate concrete.

Map-Cracking

Map-cracking as used in this report may be defined as the type which forms a pattern of irregularly shaped blocks in the surface of the concrete. Map-cracking per se is not necessarily serious; nor does it necessarily lead to disintegration or complete failure. Some badly map-cracked pavements have proved durable under severe weathering conditions. However, when map-cracking is accompanied by other evidences of abnormal expansion, deep scaling, or unsoundness, as revealed by a lack of ring under the hammer, it can be generally assumed to be of the progressive type. An advanced stage of map-cracking of this type is shown in figure 1. Such a condition is evidence of disintegration even though under favorable conditions it may be possible to maintain traffic over the road for many years without the necessity of making extensive repairs or replacements.

The fact that map-cracking sometimes develops on roads carrying comparatively light traffic would indicate that the fundamental causes underlying the initial cracking are independent of this factor. The primary cause appears to be excessive and abnormal expansion of the concrete. Evidence of this is found in the closed expansion joints which usually accompany the appearance of map-cracking. Furthermore, this expansion seems to be confined to the sand-gravel concrete, being almost entirely absent on pavements containing the conventional fine-and-coarse aggregate type of concrete.

Object of the Investigation

One of the objects of this investigation was to determine whether the characteristic map-cracking which is frequently associated with the use of sand-gravel as total aggregate could be reproduced in the laboratory. As early as 1938 Gibson had shown that this type of failure could be developed in the laboratory by subjecting specimens of concrete to alternations of heating and cooling and wetting and drying without the introduction of a freezing cycle. It was considered desirable to continue the line of attack suggested by Gibson by making a series of tests which would include, in addition to the Platte River aggregate, materials from two other sources differing widely from it and from each other in mineral composition. It was also considered desirable to study the behavior of concrete containing these other materials when graded exactly the same as the Platte River aggregate. In addition, the tests were planned to compare the behavior of concrete containing the Platte River material with sufficient added crushed limestone to make a conventional total aggregate gradation, with that of concrete of the same proportions containing the other two aggregates. Complete descriptions of the materials, the mix data, and the weathering cycles used in the study follow.

Cements and Aggregates

Thirty-six combinations of materials involving four cements and three aggregates in each of three gradations were used in these tests. The cements were chosen to give a considerable range in chemical composition, particularly with respect to the percentage of computed tricalcium aluminate (C_3A). The results of physical tests and chemical analyses of the cements are given in table 1. Major differences in the cements were as follows:

Cement 1.—A.S.T.M. type I, with 9 percent tricalcium aluminate (C_3A), low autoclave expansion, high Merriman sugar-test value, 0.70 percent total alkali, and 0.52 percent water-soluble alkali.

Cement 2.—A.S.T.M. type I, with 16 percent tricalcium aluminate (C_3A), relatively high autoclave expansion, high sugar-test value, 0.73 percent total alkali, and 0.38 percent water-soluble alkali.

Cement 3.—A.S.T.M. type II, with 5 percent tricalcium aluminate (C_3A), low sugar-test value, low autoclave expansion, 0.47 percent total alkali, and 0.18 percent water-soluble alkali. Cement 3, in addition to meeting the A.S.T.M. requirements, also met the requirements of the New York City Board of Water Supply. It would therefore be classified as a "Merriman" cement.[4]

Cement 4.—A.S.T.M. type II with 7 percent tricalcium aluminate (C_3A), low sugar-test value, low autoclave expansion, 0.57 percent total alkali, and 0.21 percent water-soluble alkali. Cement 4 was also classified as a Merriman cement.

It will be observed from table 1 that cement 2 has a considerably higher autoclave expansion than the other three. It is also the coarsest in terms of specific surface. It is of interest that cements 2 and 3 were from the same mill, the former being the regular commercial product and the latter a cement modified to meet the requirements of the New York Board of Water Supply. It should be noted that this work was initiated before the question of an alkali-aggregate reaction as possibly contributing to map-cracking had been raised. For this reason no attempt was made to secure wide variations in the alkali contents of the four cements.

The physical properties of the aggregates are given in tables 2 and 3 and the mineral composition of the various size fractions in table 4. All three of the aggregates met the conventional A.S.T.M. physical test requirements for concrete aggregates. A general description of the aggregates follows:

Aggregate A. — Sand-gravel from the Platte River at Schuyler, Nebr., composed essentially of granite, quartz, and feldspar, with about 0.3 percent material classified as opal. The amount of feldspar, predominantly potash (orthoclase and microcline), varied widely in the different sizes from a high of 40 percent in the No. 4–8 sieve size to a low of 3 percent in the material passing the No. 100 sieve. This aggregate has, in general, a poor service record.

Aggregate B.—Sand and gravel from Long Island, N. Y., (the so-called "Cowe Bay" material). The sand and gravel were almost entirely siliceous, being composed of about 90 percent quartz and quartzite, with practically no feldspar. This aggregate has an excellent service record.

Aggregate C.—Sand and gravel from Plainfield, Ill., in the Chicago area. In contrast with aggregate B, it was almost entirely dolomitic in composition, the sand being about 80 percent and the gravel about 90 percent dolomitic material. About 15 percent of the sand was quartz. This aggregate also has an excellent service record.

Grading and Proportioning

Three different aggregate gradations were investigated. Sieve analyses of the various aggregates and aggregate combinations are

Table 5.—*Mix data*[1]

Cement and aggregate	Proportions by—		Actual cement content (sacks per cu. yd.)	Net water content (gal. per sack)	Weight of fresh concrete (lb. per cu. ft.)
	Dry weight	Absolute volume			
SERIES I, GRADING 1					
1–A	1:4.10	1:4.92	7.4	5.0	143
1–B	1:3.73	1:4.43	7.9	5.0	143
1–C	1:3.39	1:4.05	8.5	5.0	145
2–A	1:3.83	1:4.60	7.7	5.0	142
2–B	1:3.15	1:3.74	8.7	5.0	140
2–C	1:2.98	1:3.56	9.2	5.0	143
3–A	1:4.01	1:4.82	7.6	5.0	144
3–B	1:3.44	1:4.08	8.3	5.0	142
3–C	1:3.30	1:3.94	8.6	5.0	145
4–A	1:4.12	1:4.95	7.4	5.0	143
4–B	1:3.61	1:4.28	8.0	5.0	140
4–C	1:3.30	1:3.94	8.6	5.0	144
SERIES I, GRADING 2					
1–A	1:4.04	1:4.86	7.5	5.0	144
1–B	1:3.53	1:4.20	8.1	5.0	141
1–C	1:3.10	1:3.70	9.0	5.0	145
2–A	1:3.62	1:4.35	8.1	5.0	143
2–B	1:3.02	1:3.59	9.0	5.0	140
2–C	1:2.71	1:3.24	9.8	5.0	143
3–A	1:3.87	1:4.65	7.8	5.0	144
3–B	1:3.30	1:3.91	8.6	5.0	142
3–C	1:3.17	1:3.79	8.9	5.0	145
4–A	1:4.13	1:4.96	7.4	5.0	144
4–B	1:3.50	1:4.15	8.2	5.0	140
4–C	1:2.93	1:3.49	9.3	5.0	143
SERIES II, GRADING 1[2]					
1–A	1:4.10	1:4.92	7.4	5.0	142
1–B	1:4.10	1:4.86	7.2	5.8	140
1–C	1:4.10	1:4.89	7.2	6.3	144
2–A	1:3.83	1:4.60	7.8	5.0	143
2–B	1:3.83	1:4.55	7.4	6.0	139
2–C	1:3.83	1:4.57	7.5	6.1	143
3–A	1:4.01	1:4.82	7.6	5.0	144
3–B	1:4.01	1:4.76	7.2	6.1	140
3–C	1:4.01	1:4.79	7.3	6.4	143
4–A	1:4.12	1:4.95	7.3	5.0	141
4–B	1:4.12	1:4.89	7.0	5.9	138
4–C	1:4.12	1:4.92	7.0	6.7	142
SERIES II, GRADING 2[2]					
1–A	1:4.04	1:4.86	7.5	5.0	144
1–B	1:4.04	1:4.80	7.2	6.0	140
1–C	1:4.04	1:4.83	7.2	6.4	143
2–A	1:3.62	1:4.35	8.1	5.0	143
2–B	1:3.62	1:4.29	7.8	5.8	139
2–C	1:3.62	1:4.32	7.8	6.1	142
3–A	1:3.87	1:4.65	7.8	5.0	144
3–B	1:3.87	1:4.60	7.4	5.9	140
3–C	1:3.87	1:4.62	7.5	6.1	143
4–A	1:4.13	1:4.96	7.4	5.0	143
4–B	1:4.13	1:4.90	7.0	6.1	138
4–C	1:4.13	1:4.93	7.1	6.4	142
SERIES I AND II, GRADING 3					
1–A	1:2.53:4.49	1:3.04:5.43	5.1	6.1	152
1–B	1:2.43:4.49	1:2.86:5.37	5.1	6.0	151
1–C	1:2.43:4.49	1:2.92:5.31	5.1	6.3	154
2–A	1:2.53:4.49	1:3.04:5.43	5.1	5.8	152
2–B	1:2.43:4.49	1:2.86:5.37	5.1	6.0	151
2–C	1:2.43:4.49	1:2.92:5.31	5.1	6.6	153
3–A	1:2.53:4.49	1:3.04:5.43	5.1	6.1	152
3–B	1:2.43:4.49	1:2.86:5.37	5.1	6.0	152
3–C	1:2.43:4.49	1:2.92:5.31	5.1	6.5	153
4–A	1:2.53:4.49	1:3.04:5.43	5.1	5.8	152
4–B	1:2.43:4.49	1:2.86:5.37	5.1	6.0	150
4–C	1:2.43:4.49	1:2.92:5.31	5.1	6.5	152

[1] Slump for gradings 1 and 2 in both series was approximately 1 inch; for grading 3, 2½ inches. Fineness modulus was 3.75 for grading 1, 3.35 for grading 2, and 5.84 for grading 3.

[2] In the case of aggregate A (Platte River) for Series II, the proportions and water content for each cement and grading are the same as was used for the corresponding combinations in series I. In the case of aggregates B (Long Island) and C (Chicago), the proportions were the same as were used for the corresponding combinations involving aggregate A. The water content was varied to maintain the desired slump.

[4] The term "Merriman" cement is frequently used to define portland cement that will meet the specifications of the Board of Water Supply of the City of New York, edition of 1937. These specifications, which contain certain special requirements not found in the A.S.T.M. specifications, were developed by the late Thaddeus Merriman, consulting engineer for the Board for many years. Mr. Merriman felt that his special requirements were necessary in order to insure proper burning, thereby insuring a more volume constant and a more durable product.

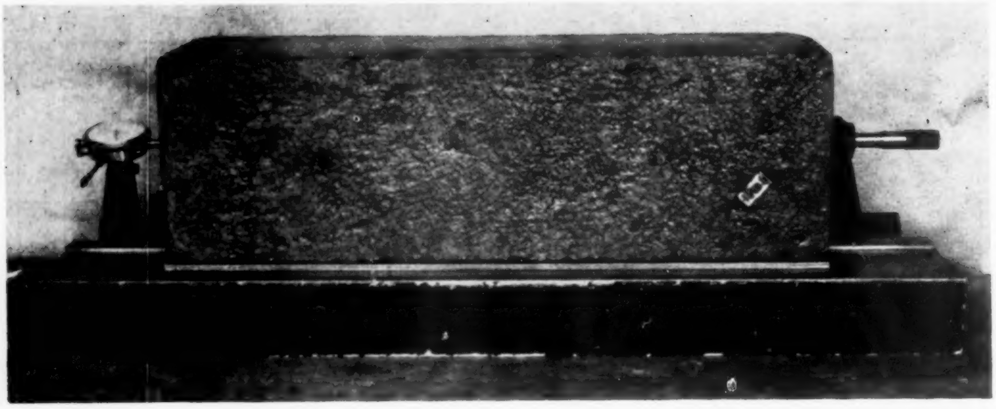

Figure 2.—Horizontal comparator with test specimen.

given in table 2. A summary of the gradings follows:

Grading 1.—The gradation of the Platte River sand-gravel as normally used: In reality a coarse sand, only 5 percent being retained on the ⅜-inch sieve and only 5 percent passing the No. 50 sieve.

Grading 2.—The same as grading 1 but with sufficient fines added (from the same source) to bring the total passing the No. 50 sieve up to 20 percent. The maximum size was not increased.

Grading 3.—A conventional aggregate gradation, from 1½-inch size down, with 64 percent retained on the No. 4 sieve. For aggregate A this was accomplished by adding crushed limestone (1½-inch to ⅜-inch in size) from Bethany Falls, Kans., to the Platte River material (a procedure locally known as "sweetening"), resulting in a combined aggregate consisting of 53 percent limestone and 47 percent sand-gravel by weight. For aggregates B and C the total aggregate was obtained by using gravel from the same source as the sand, the gradings being practically identical with that used for aggregate A combined with the crushed limestone.

Each of the four cements and three aggregates was tested in each of the three gradations, making 36 combinations in all. Two series of tests were run and two specimens were cast for each combination in each series, making a total of 144 specimens in the entire program.

In test series I, for gradings 1 and 2 the proportions were determined on the

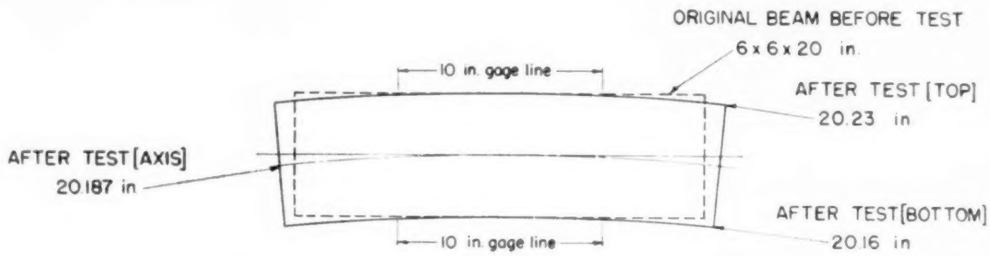

Figure 3.—Exaggerated sketch of test beam after various exposure cycles, showing typical expansions.

Table 6.—*Cumulative changes in length[1] after various storage periods*

Cement and aggregate	Test Series I: Percentage change in length after storage of—					Test Series II: Percentage change in length after storage of—				
	160 days (cycle A)	360 days (cycle B)	660 days (cycle C)	2,450 days (cycle D)	3,270 days (cycle E)	160 days (cycle A)	360 days (cycle B)	660 days (cycle C)	2,450 days (cycle D)	3,270 days (cycle E)
GRADING 1										
1-A	−0.005	0.001	0.772	0.940	0.968	−0.009	−0.002	0.752	0.952	0.976
1-B	−.005	−.002	.044	.108	.096	−.010	−.001	.102	.172	.169
1-C	−.017	−.010	.010	.038	.003	−.019	−.003	.016	.023	.001
2-A	−.005	.008	.118	.156	.143	−.010	.007	.124	.176	.147
2-B	−.008	.002	.038	.047	.034	−.011	.006	.022	.028	.017
2-C	−.019	−.006	.015	.052	.013	−.027	−.007	.011	.016	−.002
3-A	−.010	−.011	.223	.459	.508	−.009	−.005	.445	.648	.686
3-B	−.012	−.013	.010	...	...	−.017	−.005	.019	.032	.013
3-C	−.017	−.012	.006	.036	.004	−.023	−.003	.016	.023	.004
4-A	−.010	−.005	.316	.529	.548	−.015	−.010	.106	...	...
4-B	−.016	−.011	.009	.043	.017	−.013	−.004	.017	.020	.004
4-C	−.022	−.015	−.002	.010	−.006	−.028	−.013	−.005	0	−.001
GRADING 2										
1-A	−0.010	0	0.498	0.605	.607	−0.010	−0.006	0.646	0.720	0.728
1-B	−.007	−0.004	.033	.072	.059	−.010	−.001	.041	.042	.057
1-C	−.018	−.015	.011	.026	0	−.019	−.011	.013	.019	0
2-A	−.006	.002	.082	.098	.093	−.015	.001	.115	.148	138
2-B	−.012	.003	.033	.060	.039	−.014	.002	.030	.039	.035
2-C	−.022	−.010	.018	.041	.010	−.021	−.006	.022	.036	.012
3-A	−.013	−.017	.030	.095	.099	−.020	−.019	.144	.204	.195
3-B	−.020	−.017	.012	.057	.045	−.017	−.006	.022	.033	.012
3-C	−.015	−.014	.010	.026	.009	−.021	−.008	.010	.013	.003
4-A	−.016	−.015	.008	.038	.011	−.015	−.014	.027	.041	.020
4-B	−.013	−.016	.007	.019	.008	−.019	−.010	.010	.019	.005
4-C	−.021	−.016	.003	.014	−.001	−.020	−.007	.008	.013	.001
GRADING 3										
1-A	−0.003	−0.001	0.022	0.042	0.033	−0.001	0.006	0.035	0.047	0.041
1-B	−.004	−.004	.062	.187	.163	−.006	.002	.101	.169	.184
1-C	−.004	.002	.009	.024	.016	−.012	.006	.019	.020	.013
2-A	−.004	0	.012	.107	.081	−.005	.003	.023	.108	.103
2-B	0	.004	.024	.072	.078	−.007	.004	.030	.068	.075
2-C	−.007	−.005	.007	.043	.014	−.018	−.003	.016	.029	.012
3-A	−.008	−.006	.005	.014	.009	−.007	.001	.016	.025	.018
3-B	−.010	−.003	.016	.030	.023	−.012	0	.028	.032	.032
3-C	−.013	−.001	.008	.027	.016	−.015	.001	.015	.017	.016
4-A	−.009	−.003	.004	.010	.007	−.009	−.002	.012	.015	.019
4-B	−.006	.001	.039	.046	.033	−.013	−.004	.014	.019	.010
4-C	−.009	−.001	.002	.013	.007	−.014	−.002	.014	.014	.011

[1] Each value is the average of tests of two beams.

basis of an approximately constant slump and a constant water-cement ratio of 0.67 by volume (5.0 gallons per sack), for all combinations of cements and aggregates. This resulted in average cement contents of about 7.6 sacks per cubic yard for the Platte River material, or about the same as used in the roads which had given trouble. The corresponding cement factors for aggregates B and C were considerably higher, averaging about 8.4 for aggregate B and 9.0 for aggregate C. For both gradings 1 and 2 a slump of approximately 1 inch was used, as this is the consistency normally employed in actual construction with sand-gravel aggregate.

In test series II, for gradings 1 and 2 identical proportions (by weight) and consistency were used for all three aggregates and a given cement as were used in series I with that same cement and the Platte River material (aggregate A). This was for the purpose of equalizing somewhat the variations in cement content which resulted from the use of a constant water-cement ratio in test series I. The resultant water-cement ratios in test series II varied considerably, running as high as 6.7 gallons per sack as compared to the 5.0 gallons per sack used in all mixes containing the Platte River material.

For grading 3 (the normal concrete grading) in both test series I and II, the combinations were proportioned on the basis of an approximately constant cement factor of 5 sacks per cubic yard, with the slump maintained at approximately 2½ inches.

It will be seen from the foregoing that, for each variable involving aggregate A in gradings 1 and 2, results based on four specimens of a kind (two in series I and two in series II) were obtained as compared to two specimens of a kind in the case of aggregates B and C. Thus, for aggregate A, series II served as a check on series I. For grading 3, all of the data from series II served as a check on series I inasmuch as the same mixes were used for both. Complete mix data are given in table 5.

Mixing and Storage

Aggregates in gradings 1 and 2 and the fine aggregate fraction of grading 3 contained some free water at the time of mixing. The coarse aggregates used in grading 3 were in a saturated and surface-dry condition at time of use. The necessary corrections for free water were made when computing the net water-cement ratios. Mixing was done in an open-pan Lancaster mixer, sufficient concrete for one 6 by 6 by 20-inch specimen being mixed at one time. One specimen for each of the three aggregates, the three gradings, and two of the four cements was made on each working day, making 18 specimens per day, or a total of 144 specimens in 8 working days. All specimens containing the ⅜-inch maximum size aggregate (gradings 1 and 2) were molded by thoroughly spading the concrete with a trowel, as it was found that the standard rodding procedure was not satisfactory for these mixtures. Specimens of normal concrete (grading 3) were molded by rodding in the standard manner. The consistency was not controlled directly by the use of the slump test but was judged by means of the flow test. The concrete mixes were adjusted to provide a consistency corresponding to approximately a 1-inch slump for gradings 1 and 2 and a 2½-inch slump for grading 3. All specimens were cured 1 day in the molds in the mixing room and 27 days in the moist room, prior to testing.

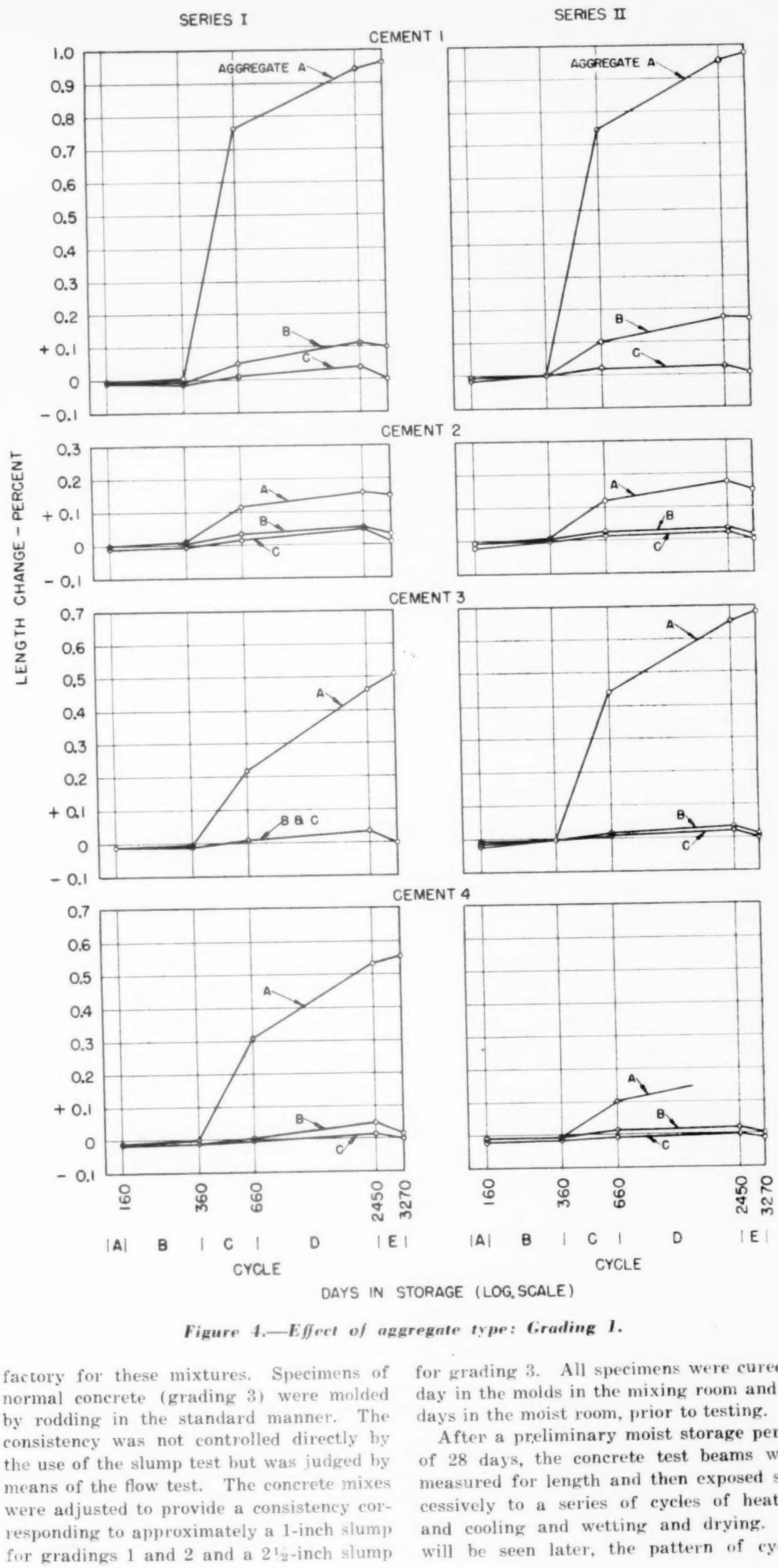

Figure 4.—Effect of aggregate type: Grading 1.

After a preliminary moist storage period of 28 days, the concrete test beams were measured for length and then exposed successively to a series of cycles of heating and cooling and wetting and drying. As will be seen later, the pattern of cycles

was established during the course of the work, as need for change in procedure was evidenced. The complete series of cycles was as follows:

Cycle A.—One day in moist room at 70° F., followed by 1 day in air at 130° F., followed by 2 days in air at 70° F.: 40 cycles, requiring 160 days.

Cycle B.—One day in water at 70° F., followed by 1 day in air at 130° F., followed by 2 days in air at 70° F.: 50 cycles, requiring 200 days.

Cycle C.—One day in water at 70° F., followed by 1 day in air at 130° F.: 150 cycles, requiring 300 days.

Cycle D.—Continuous storage in moist air at 70° F. for 1,790 days (approximately 5 years).

Cycle E.—Exposure outdoors near Washington, D. C., for 820 days (approximately 2¼ years), followed by 4 days resaturation in water.

Measurements

The test specimens used in this study were concrete beams 6 by 6 by 20 inches in size. Stainless steel plugs were set in the center of each end of the specimens and brass inserts, provided with drilled gage seats, were set in the upper and lower surfaces. Three sets of length-change readings were taken—one on the end plugs and the others along the upper and lower surfaces of the specimens. These latter measurements were made with a mechanical strain gage over a 10-inch gage length; the end measurements were made with a horizontal comparator reading to 0.0001-inch. The comparator is shown in figure 2. All measurements were taken with the concrete in a moist condition at 70° F. in order to eliminate insofar as possible differences due to variations in temperature and moisture conditions at the time of test.

In general the surface measurements showed the same trends as those taken along the central axis. However, the surface measurements, which were made with a mechanical strain gage over a gage length of 10 inches, were somewhat erratic. The end measurements were made with a horizontal comparator over the entire 20-inch length of the beam and were quite consistent. The individual discrepancies noted in the surface readings reveal the difficulty of securing consistent results with a mechanical strain gage, which involves the personal equation. With the horizontal comparator, on the other hand, very consistent results are obtainable because the personal equation is absent.

Discussion of Observations

The surface measurements, though erratic, do indicate two definite trends, neither of which would have been revealed by end measurements. During cycle D (continuous moist storage for 1,790 days) the surface measurements revealed appreciable warping in many of the specimens, particularly those which had developed large residual expansions at the end of cycle C. These were principally the combinations involving aggregate A (the Platte River material) in gradings 1 and 2. The over-all expansion of these specimens at the end of cycle D was also large. In other words, they continued to expand after the wetting and drying cycle had been discontinued.

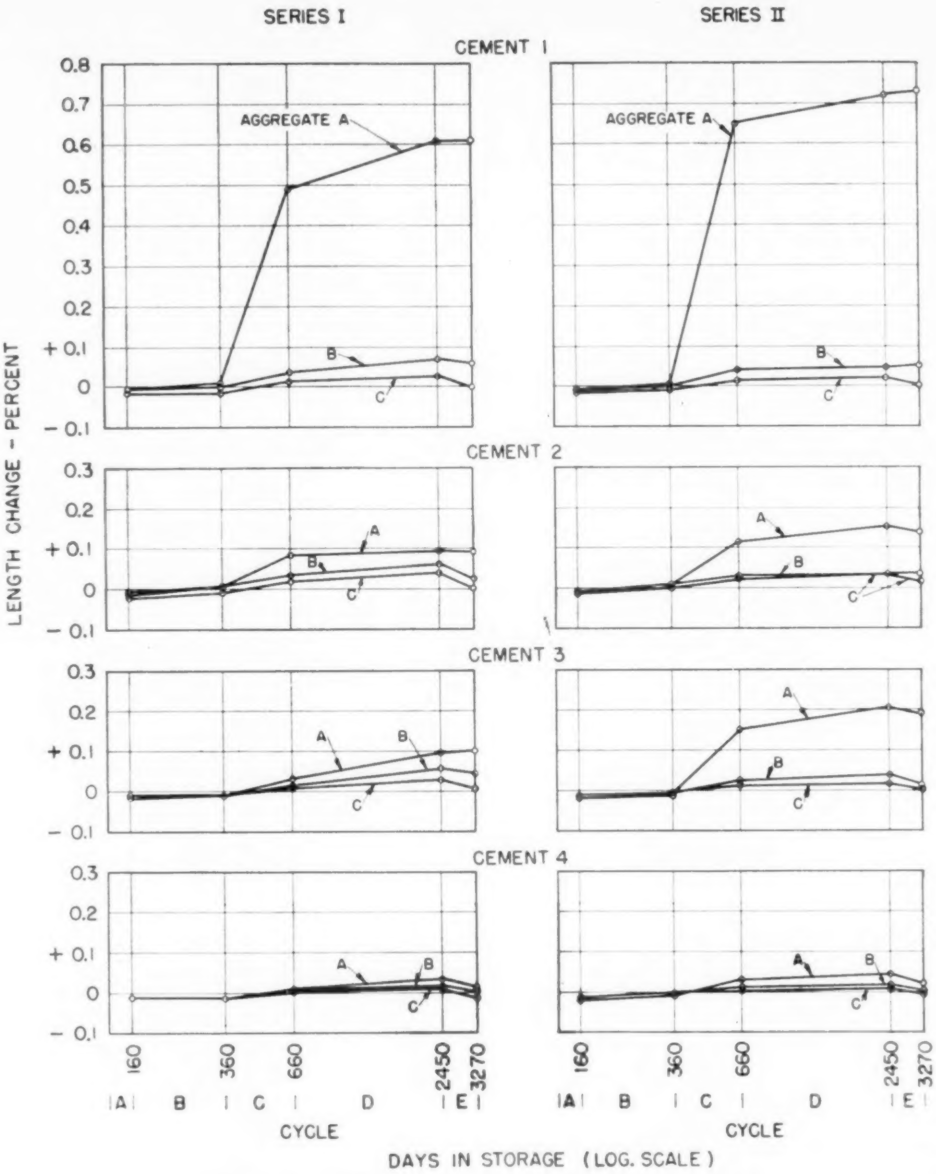

Figure 5.—Effect of aggregate type: Grading 2.

Warping was revealed by substantially higher expansion along the top surface than along the lower surface. This caused the ends to curl downward, as illustrated in figure 3, which shows readings for one of the beams in the combination of aggregate A (in grading 1) with cement 1. These measurements no doubt reflected the tendency of the surface mortar to expand at a greater rate than the mass of the concrete. Such a tendency probably exists in most concrete pavements because, due to finishing operations, a layer of mortar of distinctly inferior quality is formed on the surface of the pavement. These length differentials between the upper and lower surfaces were found only in the combinations which had expanded excessively. Where the overall expansions were small (0.1 percent or less), which was the case with the majority of the combinations, the warping tendency was not indicated by the measurements. This was due, it is believed, to the fact that the surface measurements were not sufficiently precise to reveal the very small length changes involved.

Another interesting trend was the upward warping at the ends of most of the specimens at the end of cycle E (outdoor storage on the ground for 2¼ years). This warping was probably due to differential drying out of the top surface with respect to the lower surface, since the latter was in contact with the ground. Here again, however, the individual results show many inconsistencies. Although the general trends indicated by the surface measurements are probably bona fide, it is believed the individual measurements, for the reasons stated, are not sufficiently accurate to permit detailed comparisons between combinations where the total movements are small.

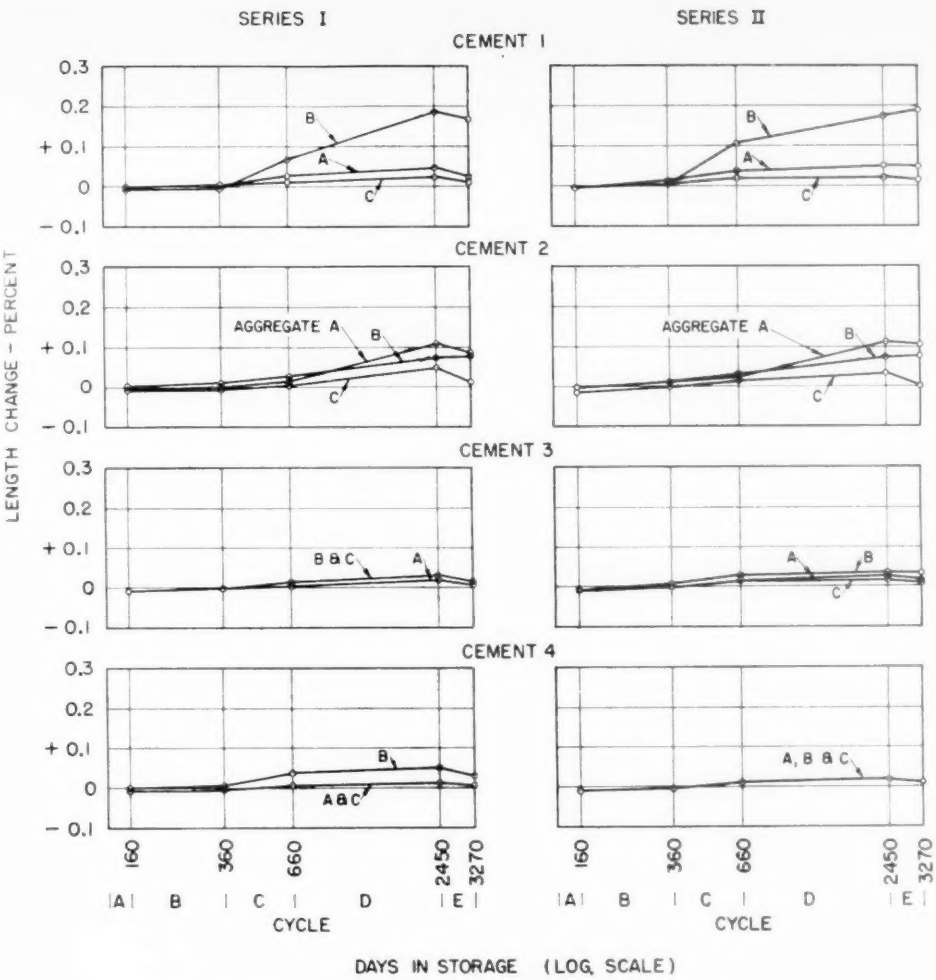

Figure 6.—Effect of aggregate type: Grading 3.

These include most of the combinations involving aggregates B and C as well as aggregate A in grading 3. For this reason these data are omitted and the balance of the report will be limited to a discussion of the end measurements only.

The cumulative percentage changes in length of the test specimens along the central axes, at the expiration of the various exposure periods, are given in table 6 and are plotted in figures 4–7. Each value is the average of measurements on two specimens made on different days. In the case of aggregate A in gradings 1 and 2, and all three aggregates in grading 3, the same proportions and consistency were used in both test series I and II. In this case, therefore, the results of the two series are directly comparable, a point which should be borne in mind when studying the data. On the other hand, combinations involving aggregates B and C in gradings 1 and 2 are not strictly comparable in the two series due to the fact that a constant water-cement ratio was used in series I whereas in series II the weight proportions were kept constant for each cement. Even in these cases, however, reference to the data will show that the differences in cement content and water content, although quite large, were apparently not sufficiently great to affect the general trends to an appreciable extent.

At the end of cycle A (160 days), it was found that all of the specimens were showing small residual contractions. This indicated quite definitely that 24 hours in the moist room was not long enough to insure complete resaturation after drying at 130° F. Cycle B was therefore introduced, to provide for immersion in water instead of storage in the moist room. After 50 alternations of cycle B, however, the net expansions were still found in all cases to be very small.

Cycle C was then instituted, omitting altogether the 48-hour storage period in air at 70°F. Under this procedure the specimens were immersed immediately in water upon removal from the drying oven at 130° F., thus simulating the effect of a sudden cool shower upon a concrete pavement at the close of a hot dry day. This treatment had the effect desired: It differentiated quite definitely between the concretes in a manner similar to that observed in service.

Cycle C was continued for 300 days. Abnormal expansion (an increase in length of almost 1 percent in certain cases) had developed in some of the Platte River sand-gravel combinations by that time, with resultant map-cracking and other evidences of deterioration. This indicated the desirability of discontinuing the type of cycle which involved daily handling of the specimens. They were therefore stored in the moist room for approximately 5 years (cycle D), after which they were again measured for length and then stored outdoors on the ground in the vicinity of the laboratory (cycle E). The final set of readings was taken after about 2¼ years of storage outdoors, at which time the specimens were approximately 9 years old.

Effect of Aggregate in Grading 1

Figure 4 shows for grading 1 and for each cement the effect of aggregate type on length change. It will be seen that the various combinations involving aggregate A, all of which showed relatively high expansion at the end of cycle C, continued to expand through cycle D and, in most cases, through cycle E. The concrete containing cement 2 is the only exception to the latter tendency. On the other hand, the concretes containing aggregates B and C, although showing small additional expansions at the end of cycle D, all contracted as the result of the outdoor exposure of cycle E. These facts would indicate that whatever the nature of the internal reactions which caused the excessive expansion with aggregate A, the same reactions were continuing through cycle E. Otherwise, contractions would be expected during cycle E similar to those shown in the case of aggregates B and C.

It should also be noted that the amount of the expansion occurring in the concrete containing aggregate A was influenced appreciably by the cement, cement 1 being by far the most active and cement 2 the least active of the four. When studying figure 4, it is important to remember that, insofar as aggregate A is concerned, the proportions used in series II were identical with those used in series I, although an interval of nearly a month elapsed between the casting of the specimens in the two series. The similarity of the trends as revealed in the two series is quite striking and tends to show that the trends shown in series I were not accidental.

It should be observed, also, that the influence of aggregate grading has been entirely eliminated by this grouping of the data since all of the specimens, regardless of aggregate type, contain material of identical grading (in this case grading 1, the normal grading of the Platte River material). The data show conclusively that aggregate grading is not responsible for the excessive expansions which have taken place.

As noted above, all of the concretes containing aggregates B and C expanded somewhat during cycle D and then showed contraction at the end of cycle E. Furthermore, aggregate B, the siliceous material from Long Island, consistently showed higher expansions than aggregate C, the dolomitic material from Chicago. There is a strong possibility that these differences, although small as compared to the expansions found in the case of aggregate A, may be related to differences in the thermal

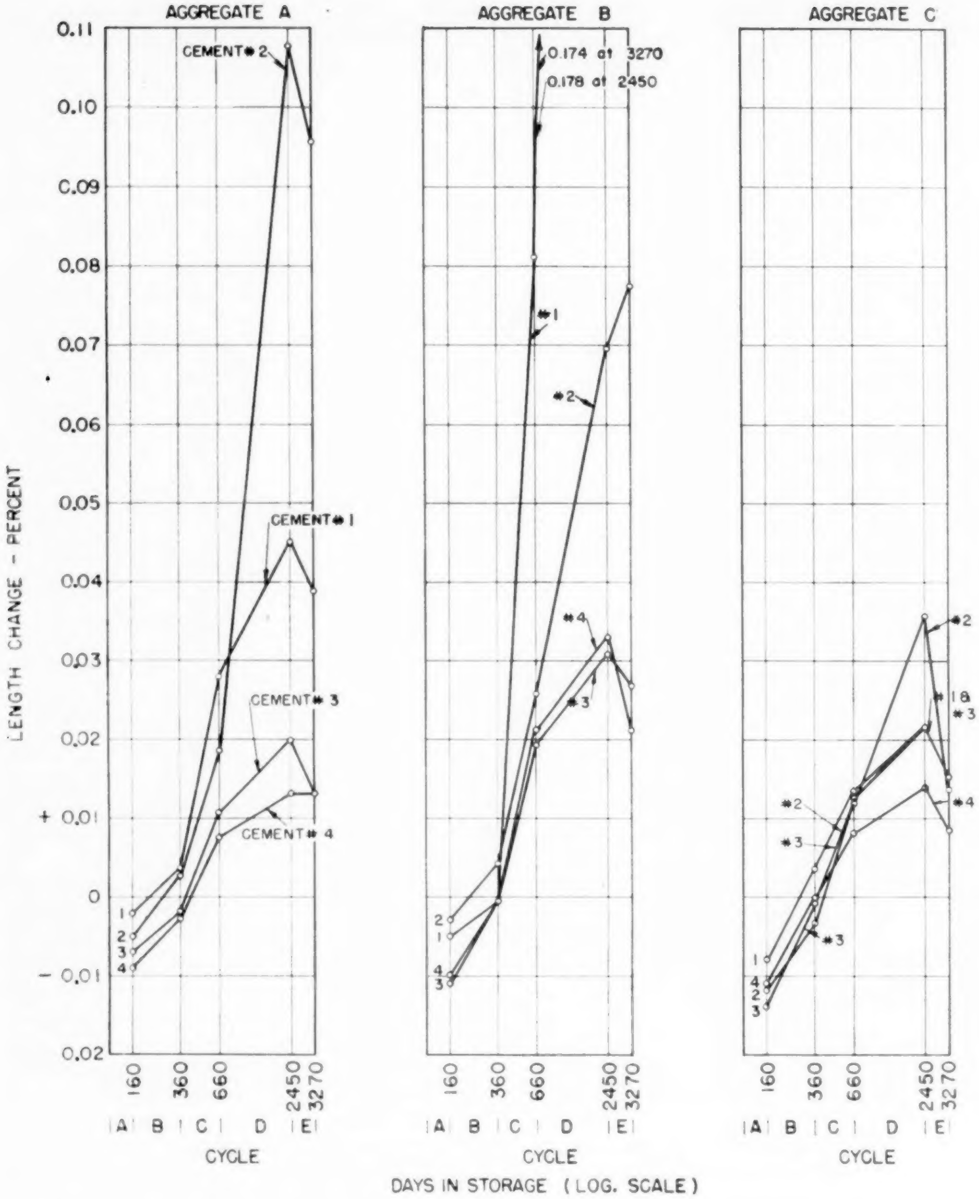

Figure 7.—Effect of cement: Grading 3 (average for tests series I and II).

characteristics of the two aggregates. However, there is no evidence of abnormal growth with either of these materials. The maximum expansions with all but one cement were less than the 0.1 percent, which is frequently indicated as the dividing line between normal and abnormal behavior in this regard.

The reason for the abnormal expansions found with the Platte River material remains unknown. There is the possibility of a slight alkali-aggregate reaction, but the fact that the Platte River aggregate used in these tests contained only 0.3 percent opal, coupled with the lack of relation between the alkali contents of the four cements and the resultant volume change, would tend to minimize this possibility. Neither can these abnormal expansions be due to the rich mix that was used, because in series I the cement contents of the combinations involving aggregates B and C were actually higher than those which involved aggregate A.

There remains the possibility that these abnormal effects are due to differential thermal characteristics of the aggregates. Blanks[5] has called attention to the fact that aggregate of the same general nature as the Platte River material contains substantial amounts of the orthoclase and microcline feldspars and that these minerals have a very low thermal coefficient of expansion. The Platte River gravel used in these tests contained varying amounts of these minerals, ranging up to as much as 40 percent in the Nos. 4–8 sieve size. It is possible that the deterioration of concrete containing this material may be due, at least in part, to stress developed within the concrete as the result of thermal incompatibility. This fact alone, however, would not account for the wide differences in expansion noted with the different cements. These differences must be related to some characteristic or characteristics of the combination which are influenced by both the aggregate and the cement. Whether these effects are physical or chemical, or a combination of the two, has not been determined.

Effect of Aggregate in Grading 2

Figure 5 shows, for each cement, the effect of aggregate type when used in grading 2. This grading was the same as grading 1 except that sufficient fine material from the same source was added to increase the total amount passing the No. 50 sieve from 5 percent to 20 percent, with no increase in the amount retained on the ⅜-inch sieve.

A comparison of figures 4 and 5 indicates, for cements 1 and 2, trends almost identical in grading 2 with those found with grading 1. In the case of cement 1, the addition of fines, while causing some reduction, did not appreciably decrease the excessive expansion shown by aggregate A in grading 1. In the case of cement 2, about the same expansions were noted for both gradings, the values being comparatively low in both cases. In the case of cement 3 in series I, and cement 4 in both series, the abnormal expansion shown for aggregate A in grading 1 was largely eliminated. In fact, so far as cement 4 is concerned, the expansions found for all three aggregates were all well within the 0.1-percent limit previously mentioned. In other words, for this cement, as well as for cement 3 in series I, concrete containing the Platte River material in grading 2 behaved normally.

In general it may be said that the addition of fines to the Platte River material reduced the expansions somewhat, the amount of the reduction varying with the cement. Moreover, the tendency for continued expansion with cements 1, 3, and 4 during cycle E, noted in the case of grading 1, was not found with grading 2.

Attention has been called to the fact that, in series I, the cement contents of the concrete containing aggregates B and C were substantially higher than those used with aggregate A. For example, in the case of aggregate C in grading 2, cement 2 of series I (fig. 5), the cement factor was 9.8 sacks per cubic yard as compared to 9.0 for aggregate B and 8.1 for aggregate A. These values, as well as the corresponding cement factors for the other combinations used in series I, gradings 1 or 2, are shown in table 5. The variations were necessary in order to maintain the same water-cement ratio throughout the series. The data show definitely that there is no relation whatever between cement content and expansion. In fact, as will be seen later, the actual expansions of certain combinations in gradings 1 and 2, all of which involved the use of very rich mixes in series I, were no higher at any time than the expansions developed with grading 3 (the normal concrete), where the cement content was reduced to 5 sacks per cubic yard.

[5] *Modern concepts applied to concrete aggregate*, by R. F. Blanks. Proceedings of the American Society of Civil Engineers, Vol. 75, No. 4, April 1949, p. 441.

Effect of Aggregate in Grading 3

The effect of aggregate type in grading 3 with each cement is shown in figure 6. It will be noted that in practically all cases the abnormal expansions which occurred when using aggregate A in gradings 1 and 2 were eliminated by the use of a normal concrete grading obtained by mixing the Platte River material with crushed limestone. In fact, the maximum expansions with this combination were actually less in all cases, except with cement 2, than were those for the corresponding combinations involving aggregate B. In studying figure 6 it should be borne in mind that aggregate A, the Platte River sand-gravel, has been combined with crushed limestone in about equal proportions. This substantially reduced the silica content of the aggregate, which may account for the smaller expansions found in the case of aggregate A as compared to aggregate B, which was almost entirely siliceous. In the case of cement 2, both series show higher expansions for aggregate A than for either B or C. This reversal cannot be considered accidental since the results of the two series check each other almost exactly.

Effect of Cement in Grading 3

Except for the combination involving cement 1 and aggregate B, virtually all of the expansions observed in the normal concrete (grading 3) were within the range of 0 to 0.1 percent. It was decided, therefore, to plot the length changes for this grading on a very much larger vertical scale than that used in figures 4–6. In figure 7, the chart so produced, differences in expansion of the order of 0.01 percent or less are clearly indicated and may be of some interest. Each point used in plotting the curves was the average of four determinations—two in series I and two in series II. The corresponding length changes for each series separately are shown in table 6.

In studying figure 7, the nature of the various exposure cycles should be kept clearly in mind. It will be recalled that cycle A involved a 72-hour drying period followed by 24 hours in moist air. Figure 7 shows clearly that 24 hours of resaturation in moist air was not sufficient to prevent residual contraction. Furthermore, there seemed to be a definite tendency for cements 3 and 4 to show greater contractions than cements 1 and 2 (except the aggregate C–cement 2 combination), this trend being evident in the case of all three aggregates in both series. Also, for a given cement, concrete containing aggregate C showed somewhat greater contraction than the concretes in which aggregates A and B were used. At the conclusion of cycle A the moist storage condition was changed to 24 hours in water instead of in moist air, the period of drying remaining the same. At the expiration of 50 cycles of this treatment (cycle B), all of the specimens had expanded, although in most cases they still showed some residual contraction.

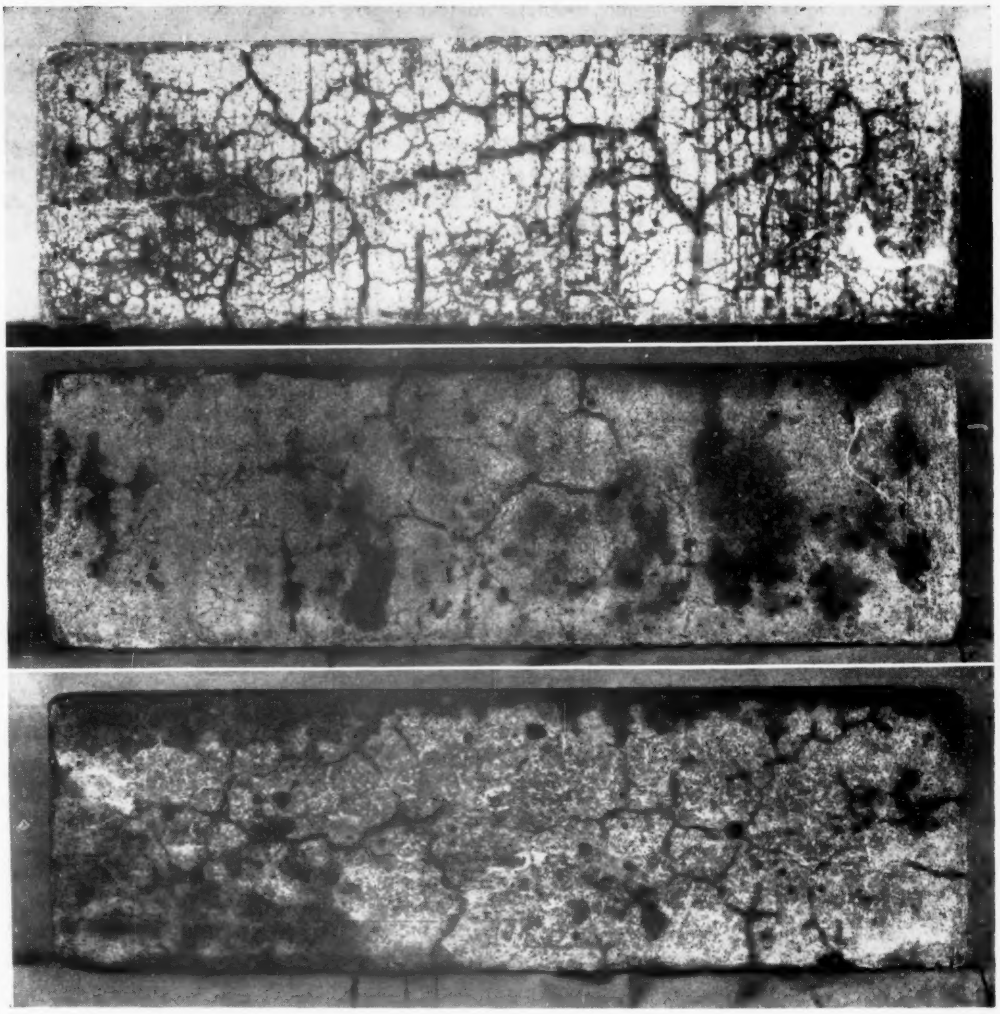

Figure 8.—Abnormal expansion of specimens containing sand-gravel aggregate: (top) grading 1 with cement 1, at end of cycle C; (center) grading 2 with cement 1, at end of cycle E; (bottom) grading 1 with cement 3, at end of cycle E.

With the elimination of the 48-hour drying period at 70°F. (cycle C), the specimens continued to expand, this trend continuing through cycle D. It will be noted that at the expiration of cycle C all combinations showed residual expansion, the amounts varying with both the cement and the aggregate. Cements 1 and 2 expanded more than cements 3 and 4, the difference being much more marked in the case of aggregates A and B than in the case of aggregrate C.

In most cases the specimens contracted during cycle E. After 2¼ years of outdoor exposure, the 96 hours in water which was provided at the end of cycle E was apparently not sufficient to resaturate the specimens. In the case of cement 2 with aggregate B, readings at the end of cycle E showed further expansion, which is a definite exception to the general trend. However, it should be noted again that the same tendency was found in both series (see fig. 6).

The chief point of interest observable in figure 7 is the relatively high expansion which took place in the combinations involving cements 1 and 2 with aggregates A and B. Aggregate A in this grading was composed of a mixture of the Platte River material and crushed limestone in about equal parts; aggregate B was almost 100 percent quartz or quartzite; and aggregate C about 95 percent dolomite. The chief difference in the cements is the fact that cements 3 and 4, in addition to meeting the standard A.S.T.M. requirements, also met the specification requirements of the New York City Board of Water Supply.

Cement meeting these requirements would be classified as A.S.T.M. type II, principally because of the limitation on alumina, but they are much more restrictive than type II in that they also include limitations on sugar solubility (a test devised by Merriman to detect underburning) as well as a requirement on maximum allowable water-soluble alkali. The authors are not prepared to advance an explanation for the increase in expansion noted in the case of cements 1 and 2 in combination with aggregates A and B as compared to the expansion noted for other combinations. However, the trends are so definite and are repeated so consistently in the two series of tests as to make it extremely unlikely that they are accidental. The data are presented as an interesting example of the

possible variations in the volume change characteristics of different combinations of cements and aggregates. They illustrate a principle which is being recognized more and more: The volume constancy of concrete is influenced to a marked degree by the particular combination of cement and aggregates used in the mix, and these materials must be studied in combination with each other in concrete rather than individually.

Examples of the excessive map-cracking which developed in many of the specimens containing aggregate A are shown in fig. 8.

Unsolved Problems

It is realized that the foregoing discussions raise many questions for which answers have not been supplied. This is just as true now as it was in 1942 when the original progress report was prepared. For example, no one, as far as the authors are aware, has yet advanced an entirely satisfactory explanation for the abnormal expansion which takes place when Platte River or similar aggregate is used in concrete with certain cements. Nor has an adequate explanation been forthcoming as to why this expansion can be stopped by the addition of crushed limestone to such aggregates.

These tests, as well as tests made by other investigators, have proved that conventional factors such as aggregate grading, aggregate quality as measured by conventional tests, cement content, free lime in cement, etc., are not sufficient to explain this abnormal expansion. The probability that the aggregate is mildly alkali-reactive, combined with the fact that from one-fourth to one-third of the aggregate consists of a type of feldspar having a low thermal coefficient of expansion, may supply the answer, but the data of these tests indicate quite definitely that neither of these facts taken separately is the answer. Moreover, the fact that the Platte River aggregate used in these tests contained only 0.3 percent opal, and insignificant amounts of other possibly reactive aggregates, would indicate that the alkali-aggregate reaction, as it is generally considered, was not an important factor.

It is also difficult to visualize the mechanics of an action which results in expansion due to the use of aggregate having a low thermal coefficient of expansion. However, there is also the possibility that the feldspar may contribute to the expansion in some other way, due possibly to alteration, with time, of its physical properties.

New Publication

A FACTUAL DISCUSSION OF MOTOR-TRUCK OPERATION, REGULATION, AND TAXATION

The Bureau of Public Roads has recently published *A Factual Discussion of Motor-truck Operation, Regulation, and Taxation*, a 113-page bulletin presenting in summary form the factual records and other data available to the Bureau, with discussions of their significance, which might prove useful in any study and investigation of the transportation problem. The bulletin may be purchased from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C., at 30 cents a copy.

The subject material in the bulletin is presented in seven parts, covering the growth of motor-vehicle registration and use, the effects of size and weight of vehicles on the geometric design and traffic capacity of highways, axle loading and its effect on roads and legal limitation, weight of vehicles and its effect on bridges, the character of overloaded vehicles and their pay loads, highway-user tax payments in relation to highway revenues and expenditures, and the allocation of highway tax responsibility. Several appendixes containing valuable information are also included.

The report was prepared at the request of the Subcommittee on Domestic Land and Water Transportation of the Committee on Interstate and Foreign Commerce, United States Senate, which was investigating problems relating to the transportation and communications industries. The report was presented before the committee in June 1950 and is reprinted from the committee's hearings, which appeared under the title *Study of Domestic Land and Water Transportation*.

Highway Soil Engineering Film

Highway Soil Engineering, a motion picture produced by the Bureau of Public Roads to illustrate field surveying and sampling and laboratory testing of soils encountered in highway construction, is now available on loan to highway departments, universities, and other organizations. The 16-millimeter film, with sound and in full color, has a running time of almost two hours. The subject treatment is technical in nature and of interest primarily to engineers and engineering students.

Highway Soil Engineering describes the two distinctive components of soil—granular and silt-clay materials—and illustrates the methods employed in surveying and sampling soils in the field. Laboratory tests are presented in sequences which show the step-by-step procedures involved. The tests demonstrated are those used by the Bureau and many of the State highway departments, and cover the complete range needed to examine the properties of soils that are of interest to highway engineers.

The picture shows the striking contrast in condition and in maintenance requirements of pavements laid on good and on poor subgrade soils. It concludes with a demonstration of the value of a sand subbase in preventing intrusion of subgrade soil into the overlying crushed-stone base course.

Highway Soil Engineering may be borrowed by any responsible organization without cost, except for the nominal transportation charges. The film may be obtained for showings by writing to the Visual Education Branch, Bureau of Public Roads, Washington 25, D. C.

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Act III.—Uniform Motor-Vehicle Civil Liability Act. 10 cents.
Act IV.—Uniform Motor-Vehicle Safety Responsibility Act. 10 cents.
Act V.—Uniform Act Regulating Traffic on Highways. 20 cents.
Model Traffic Ordinance. 15 cents.

MISCELLANEOUS PUBLICATIONS

Bibliography of Highway Planning Reports. 30 cents.
Construction of Private Driveways (No. 272MP). 10 cents.
Economic and Statistical Analysis of Highway Construction Expenditures. 15 cents.
Electrical Equipment on Movable Bridges (No. 265T). 40 cents.
Factual Discussion of Motortruck Operation, Regulation, and Taxation. 30 cents.
Federal Legislation and Regulations Relating to Highway Construction. 40 cents.
Financing of Highways by Counties and Local Rural Governments, 1931–41. 45 cents.
Guides to Traffic Safety. 10 cents.
Highway Accidents. 10 cents.
Highway Bond Calculations. 10 cents.
Highway Bridge Location (No. 1486D). 15 cents.
Highway Capacity Manual. 65 cents.
Highway Needs of the National Defense (House Document No. 249). 50 cents.
Highway Practice in the United States of America. 50 cents.
Highway Statistics, 1945. 35 cents.
Highway Statistics, 1946. 50 cents.
Highway Statistics, 1947. 45 cents.
Highway Statistics, 1948. 65 cents.
Highway Statistics, 1949. 55 cents.
Highway Statistics, Summary to 1945. 40 cents.
Highways of History. 25 cents.
Identification of Rock Types. 10 cents.
Interregional Highways (House Document No. 379). 75 cents.
Legal Aspects of Controlling Highway Access. 15 cents.
Local Rural Road Problem. 20 cents.
Manual on Uniform Traffic Control Devices for Streets and Highways. 50 cents.
Mathematical Theory of Vibration in Suspension Bridges. $1.25.
Principles of Highway Construction as Applied to Airports, Flight Strips, and Other Landing Areas for Aircraft. $1.75.
Public Control of Highway Access and Roadside Development. 35 cents.
Public Land Acquisition for Highway Purposes. 10 cents.
Roadside Improvement (No. 191MP). 10 cents.
Selected Bibliography on Highway Finance. 55 cents.
Specifications for Construction of Roads and Bridges in National Forests and National Parks (FP-41). $1.50.
Taxation of Motor Vehicles in 1932. 35 cents.
Tire Wear and Tire Failures on Various Road Surfaces. 10 cents.
Transition Curves for Highways. $1.25.

Single copies of the following publications are available to highway engineers and administrators for official use, and may be obtained by those so qualified upon request addressed to the Bureau of Public Roads. They are not sold by the Superintendent of Documents.

ANNUAL REPORTS

(See also adjacent column)

Public Roads Administration Annual Reports:
1943. 1944. 1945.

MISCELLANEOUS PUBLICATIONS

Bibliography on Automobile Parking in the United States.
Bibliography on Highway Lighting.
Bibliography on Highway Safety.
Bibliography on Land Acquisition for Public Roads.
Bibliography on Roadside Control.
Express Highways in the United States: a Bibliography.
Indexes to PUBLIC ROADS, volumes 17–19, 22, and 23.
Road Work on Farm Outlets Needs Skill and Right Equipment.

STATUS OF FEDERAL-AID HIGHWAY PROGRAM

AS OF APRIL 30, 1951

(Thousand Dollars)

STATE	UNPROGRAMMED BALANCES	ACTIVE PROGRAM											
		PROGRAMMED ONLY			PLANS APPROVED, CONSTRUCTION NOT STARTED			CONSTRUCTION UNDER WAY			TOTAL		
		Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles
Alabama	$17,376	$10,660	$5,459	329.9	$5,660	$2,810	85.8	$16,652	$8,081	405.2	$32,972	$16,350	820.9
Arizona	281	7,603	5,383	182.0	327	225	5.0	5,271	3,756	78.1	13,201	9,364	265.1
Arkansas	6,835	8,467	4,561	259.2	3,247	1,834	96.7	14,139	7,002	384.5	25,853	13,397	740.4
California	4,399	50,070	13,420	229.2	9,623	4,832	56.3	61,251	29,233	299.8	120,944	47,485	585.3
Colorado	3,595	4,798	2,712	179.2	3,165	1,604	59.4	12,673	7,054	279.1	20,636	11,370	517.7
Connecticut	3,519	6,206	3,135	23.0	2,029	1,209	2.3	6,504	3,619	8.9	14,739	7,963	34.2
Delaware	2,273	1,004	599	22.5	10	9		5,893	2,880	38.2	6,907	3,488	60.7
Florida	6,762	6,918	3,588	124.6	8,574	4,378	148.9	18,991	9,354	393.2	34,483	17,320	666.7
Georgia	6,774	11,642	5,959	155.0	11,446	4,829	116.8	29,809	14,941	675.4	52,897	25,729	947.2
Idaho	5,591	8,195	5,179	258.3	1,213	741	114.5	7,780	4,384	207.5	17,188	10,304	580.3
Illinois	18,654	39,770	21,414	347.2	31,803	15,897	400.5	50,478	26,216	311.0	122,051	63,527	1,058.7
Indiana	13,147	36,118	18,057	177.1	4,352	1,985	29.5	18,402	9,527	99.6	58,872	29,569	306.2
Iowa	2,083	13,655	6,370	621.0	11,608	5,746	514.3	13,155	6,948	309.7	38,418	19,064	1,445.0
Kansas	6,146	8,669	4,164	1,071.0	7,667	3,843	331.0	9,970	4,967	502.8	26,306	12,974	1,904.8
Kentucky	1,599	22,878	11,711	331.5	2,369	1,187	53.5	19,690	9,733	320.2	44,937	22,631	705.2
Louisiana	6,010	14,388	6,842	108.8	10,459	4,972	65.8	18,865	10,026	217.7	43,712	21,840	392.3
Maine	4,265	5,210	2,764	65.6	924	503	3.5	7,440	3,927	72.4	13,574	7,194	141.5
Maryland	5,049	4,886	2,420	19.4	3,026	1,228	15.8	12,006	5,533	41.6	19,918	9,181	76.8
Massachusetts	2,139	16,574	5,874	28.7	5,750	2,672	.3	65,663	32,528	61.9	87,987	41,074	90.9
Michigan	9,939	17,832	8,831	485.5	8,906	4,553	209.3	44,856	19,110	315.9	71,594	32,494	1,010.7
Minnesota	3,725	9,248	4,989	1,122.1	12,900	6,901	772.7	17,989	9,521	282.5	40,137	21,411	2,177.3
Mississippi	8,057	7,705	4,044	234.9	7,755	4,100	208.3	10,047	5,005	307.0	25,507	13,149	750.2
Missouri	10,393	22,791	11,712	785.8	16,692	8,475	441.4	30,126	15,919	434.7	69,609	36,106	1,661.9
Montana	6,051	14,883	8,978	564.6	3,549	2,064	61.2	13,051	7,862	268.8	31,483	18,904	894.6
Nebraska	7,785	15,300	7,993	532.8	7,240	3,586	243.1	11,818	6,217	330.1	34,358	17,796	1,106.0
Nevada	5,790	2,289	1,890	33.0	335	282	33.3	3,600	2,973	143.3	6,224	5,145	209.6
New Hampshire	2,540	2,921	1,634	25.3	959	478	8.5	4,907	2,438	42.8	8,787	4,550	76.6
New Jersey	5,058	7,598	3,799	12.5	3,341	1,670	.5	16,956	7,924	25.0	27,895	13,393	38.0
New Mexico	4,633	1,811	1,159	42.1	1,300	838	43.3	11,240	7,175	284.5	14,351	9,172	369.9
New York	46,180	49,264	26,266	133.2	16,540	7,587	20.5	109,999	51,569	241.4	175,803	85,422	395.1
North Carolina	5,303	14,467	7,168	419.7	4,321	2,095	86.3	28,495	13,766	621.1	47,283	23,029	1,127.1
North Dakota	3,362	10,963	5,613	1,762.4	5,827	2,889	449.6	5,266	2,631	439.2	22,056	11,133	2,651.2
Ohio	15,962	21,787	10,250	227.8	9,302	5,463	172.5	77,612	38,655	302.2	108,701	54,368	702.5
Oklahoma	1,462	18,543	8,683	305.9	6,899	3,746	159.2	24,435	12,298	401.4	49,877	24,727	866.5
Oregon	433	3,768	2,227	91.6	7,563	3,758	102.8	14,300	8,148	186.1	25,631	14,133	380.5
Pennsylvania	13,194	20,926	10,735	37.8	5,775	2,886	7.9	88,022	43,400	237.9	114,723	57,021	283.6
Rhode Island	1,635	5,388	2,694	43.2	1,532	766	3.0	13,900	7,068	16.0	20,820	10,528	62.2
South Carolina	2,983	11,131	5,988	190.1	2,306	1,143	44.5	9,652	5,001	264.5	23,089	12,132	499.1
South Dakota	1,177	10,719	6,242	898.9	5,041	2,768	324.0	9,573	5,891	668.4	25,333	14,901	1,891.3
Tennessee	3,988	11,481	5,615	160.2	12,102	5,825	197.9	19,793	9,198	351.4	43,376	20,638	709.5
Texas	8,482	4,771	1,796	83.9	23,197	11,673	372.5	50,460	24,057	927.0	78,428	37,526	1,383.4
Utah	2,095	5,952	4,461	144.2	1,243	924	22.9	4,661	3,397	164.1	11,856	8,782	331.2
Vermont	1,002	4,273	2,258	62.6	879	443	8.4	4,551	2,235	29.0	9,703	4,936	100.0
Virginia	5,840	24,496	12,091	657.3	7,372	3,683	199.0	15,312	7,482	283.2	47,180	23,256	1,139.5
Washington	5,173	8,196	3,058	166.7	1,919	951	44.3	20,899	10,001	116.9	31,014	14,010	327.9
West Virginia	4,406	13,172	5,225	89.3	5,467	2,738	71.7	9,237	4,662	76.9	27,876	12,625	237.9
Wisconsin	6,735	22,505	12,722	619.0	12,404	5,808	223.1	14,320	7,148	332.4	49,229	25,678	1,174.5
Wyoming	434	2,790	1,813	102.6	1,641	1,069	31.1	8,932	5,596	248.1	13,363	8,478	381.8
Hawaii	1,908	6,884	2,922	13.5	1,294	447	.5	10,584	3,913	29.9	18,762	7,282	43.9
District of Columbia	2,787	5,912	2,956	2.9	387	193	1.2	1,724	1,054	1.8	8,023	4,203	5.9
Puerto Rico	2,556	13,621	6,307	57.0	2,336	1,098	12.8	7,077	3,262	28.3	23,034	10,667	98.1
TOTAL	317,565	671,098	331,730	14,641.6	321,576	161,404	6,677.2	1,108,026	554,285	13,108.6	2,100,700	1,047,419	34,427.4

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